PRESSURE DISTRIBUTION ON BUILDINGS

EDWIN S. HOLDREDGE, Associate Research Engineer, and
BOB H. REED, Associate Research Architect

Summary Report No. 1
to the
DEPARTMENT OF THE ARMY
Camp Detrick, Frederick, Maryland
August 1956

CONTRACT NO.	PROJECT NO.
DA-18-064-CML-2566	4-11-05-008
DA-18-064-CML-35	4-11-05-008
DA-18-064-404-CML-77	4-11-05-013

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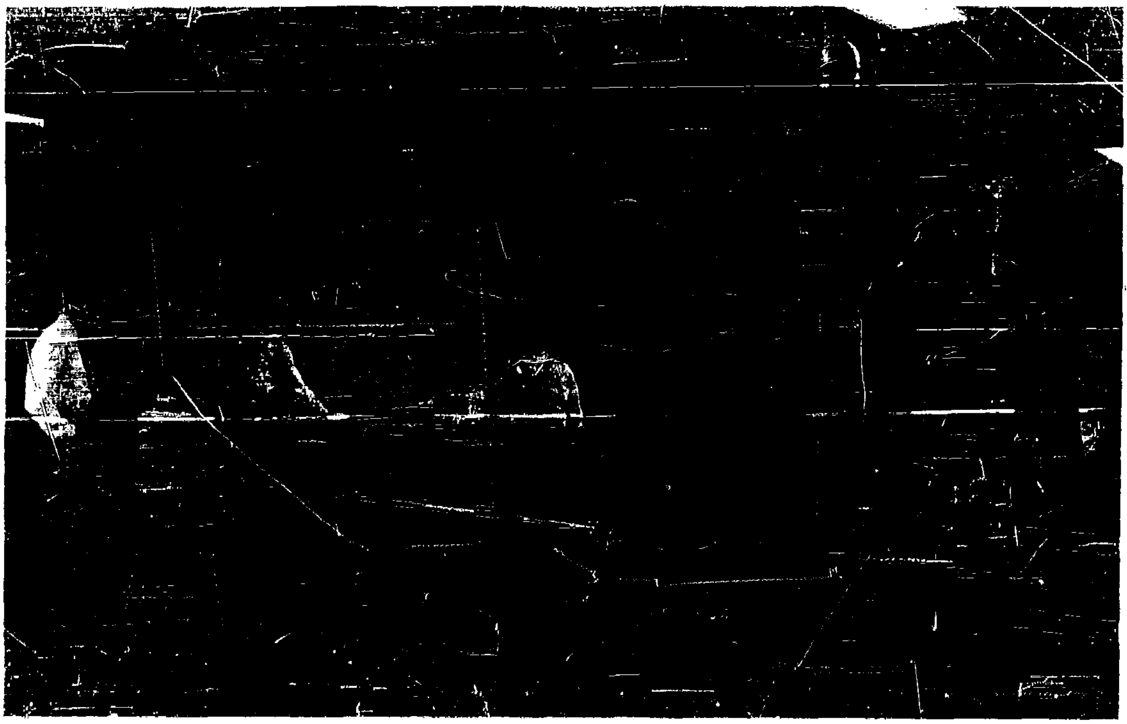
Acting Vice-Director



General view of wind tunnel being used to investigate air patterns around a model building

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INTRODUCTION

This report describes the principal work performed for the period June 15, 1954 - August 31, 1956 by the Texas Engineering Experiment Station under Contract Nos. DA-18-064-CML-2566 and DA-18-064-CML-35, Project No. 4-11-05-008, and Contract No. DA-18-064-464-CML-77, Project No. 4-11-05-013, between the Texas Agricultural and Mechanical College System as Contractor and the Department of the Army.

The referenced contracts cover investigations to determine air flow patterns and infiltration characteristics of military-type buildings by means of scale models thereof. The following items were to be studied:

1. Air flow patterns around model buildings at wind speeds ranging from approximately one to twenty mph.
2. Amount of infiltration of particulate substances such as smokes into model buildings at wind speeds ranging from one to twenty mph.
3. The minimum pressure required to prevent infiltration of particulate substances into the model buildings at wind speeds of approximately one to twenty mph and gusts up to approximately twenty mph.

THEORETICAL CONSIDERATIONS

The distribution of pressure around a building or other body immersed in a moving fluid is a function of the velocity of the fluid around the body (air pattern), which in turn is a function of the geometry of the body, the kinematic characteristics of the fluid (velocity-height distribution), and the properties of the fluid.

Air Patterns

Thus, the air pattern around a body is a function of the velocity V of the undisturbed fluid at a height y above the ground, the dimensions of the body, the density of the fluid ρ, the viscosity of the fluid μ, and the orientation of the body. For a given velocity-height distribution of the fluid and a given orientation, the variables for a rectangular building are:

Variable	Symbol	Force (F), Length (L), Time (T)	
		Dimensions	Typical Units
Velocity	V	L/T	ft/sec
Density	ρ	FT^2 / L^4	$Lb_F\ sec^2 / ft^4$
Viscosity	μ	FT / L^2	$Lb_F\ sec / ft^2$
Height	H	L	ft
Width	W	L	ft
Length	L	L	ft
General dimension of air pattern	X	L	ft

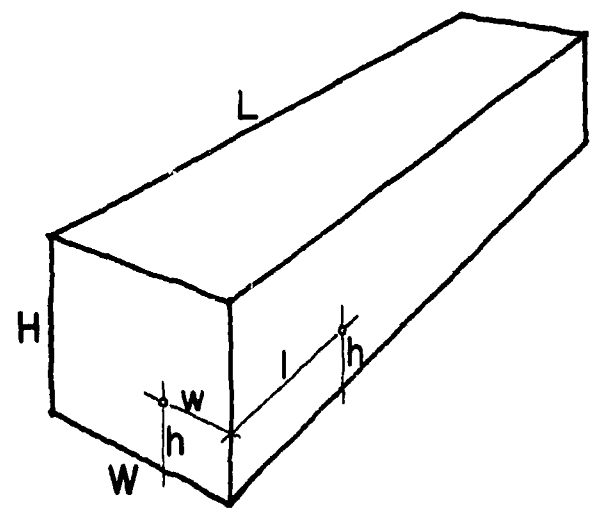
A dimensionless analysis of the variables shows that

$$\frac{X}{H} = \phi\left[\frac{HV\rho}{\mu}, \frac{L}{H}, \frac{W}{H}\right] , \qquad [1]$$

where ϕ means "function of." If the body is rectangular (i.e., not streamlined) the Reynolds Number, $\frac{HV\rho}{\mu}$, is not a necessary dimensionless group, for the viscosity governs the flow pattern (for a very wide velocity range) only for streamlined bodies. In such cases, the relationship is reduced to

$$\frac{X}{H} = \phi\left[\frac{L}{H}, \frac{W}{H}\right] \qquad [2]$$

The flow pattern relationships can be organized by plotting two of the dimensionless ratios as coordinates and the third ratio as a set of parameters.



DIAGRAMMATIC DEFINITION OF SYMBOLS

Pressure Distribution

The distribution of pressure around a building depends on the velocity of the wind V, the density of the air ρ, the viscosity of the air μ, the dimensions of the building, and the orientation of the building. For a given velocity-height distribution of the air and a given orientation, the variables for a rectangular building are:

Variable	Symbol	Force (F), Length (L), Time (T) Dimensions	Typical Units
Pressure above atmospheric pressure	P	F/L^2	Lb_F / in^2
Velocity	V	L/T	ft/sec
Density	ρ	FT^2 / L^4	$Lb_F\ sec^2 / ft^4$
Viscosity	μ	FT/L^2	$Lb_F\ sec/ft^2$
Height	H	L	ft
Distance to a point from ground	h	L	ft
Width	W	L	ft
Distance to a point from side	w	L	ft
Length	L	L	ft
Distance to a point from front	l	L	ft

A dimensionless analysis of the variables shows that

$$\frac{P}{\rho V^2/2} = \phi \left[\frac{HV\rho}{\mu}, \frac{H}{W}, \frac{L}{W}, \frac{h}{H}, \frac{l}{L}, \frac{w}{W} \right] \qquad [3]$$

For a building of given $\frac{H}{W}$ and $\frac{L}{W}$ ratios (i.e., a given shape) and a given wind orientation, the dimensionless product will be reduced to

$$\frac{P}{\rho V^2/2} = \phi\left[\frac{HV\rho}{\mu}, \frac{h}{H}, \frac{w}{W}\right] \qquad \text{for the H-W face.} \qquad [4]$$

If the body is not streamlined, the relationship is reduced to

$$\frac{P}{\rho V^2/2} = \phi\left[\frac{h}{H}, \frac{w}{W}\right] \qquad \text{for the H-W face.} \qquad [5]$$

A similar relationship exists for the other faces. The results can be organized by showing the values of $\frac{P}{\rho V^2/2}$ at given points on a face. This can be done by plotting contours of constant pressure coefficient, $\frac{P}{\rho V^2/2}$, on each face of a given shape building for a fixed wind orientation.

Internal Pressure

When a fluid is allowed to flow from one point to another, say point 1 to point 2, the total pressure drop is the sum of the pressure drops in the component parts of the path between 1 and 2. This pressure drop has been found to vary as the square of the velocity of the fluid. The pressure drop in a conduit or across a restriction can be found from the equation

$$\Delta P/\rho = CV^2 \qquad [6]$$

where C is determined by experiment and is dimensionless,
ρ is the density,
V is the velocity, and
ΔP is the pressure drop.

For flow through an orifice where the area of the orifice is small compared to the other areas, the equation becomes

$$\Delta P/\rho = V_1^2/2 \qquad [7]$$

where V_1 is the velocity in the orifice.

The pressure drop in a conduit varies directly as the length, and is usually expressed by

$$\Delta P = fL\rho V^2/2d \qquad [8]$$

where L is the length in the direction of flow,
d is a dimension normal to the flow, and
f is the friction factor (dimensionless) which is a function of the Reynolds Number.

For a building, the velocity inside would be small compared to the velocity through an opening in a wall and L/d would be approximately unity. The friction factor is approximately 0.03 for low velocities. Since V is more than 100 times the velocity inside, ΔP across an orifice is more than 10,000 times the pressure drop inside. The pressure drop between points 1 and 2 would then be the sum of the pressure drops across the restrictions, i.e.,

$$\Delta P_1 + \Delta P_2 = P_1 - P_2 \qquad [9]$$

The total pressure drop, $P_1 - P_2$, is a function of the following:

geometry of the building,
location of the opening,
velocity of the fluid,
density of the fluid, and
orientation of the building.

Since there is no accumulation of fluid in the building, the rate of flow in is equal to the rate of flow out, or

$$A_1\rho_1 V_1 = A_2\rho_2 V_2 \qquad [10]$$

where A_1 is the area of the entrance opening and A_2 that of the exit. When the density, ρ, is constant, this reduces to

$$V_2 = A_1 V_1 / A_2 \qquad [11]$$

From equations [6], [9], and [11]

$$(P_1 - P_{in}) + (P_{in} - P_2) = P_1 - P_2 = C\rho V_1^2 + C\rho V_2^2 = C\rho V_1^2 + C\rho\left[\frac{A_1 V_1}{A_2}\right]^2$$

Solving for the pressure ratio

$$\frac{P_1 - P_{in}}{P_1 - P_2} = \frac{\Delta P_1}{P_1 - P_2} = \frac{C\rho V_1^2}{C\rho V_1^2 + C\rho\left[\frac{A_1 V_1}{A_2}\right]^2} = \frac{1}{1 + \left[\frac{A_1}{A_2}\right]^2} \qquad [12]$$

Thus the pressure inside the structure is a function of the pressures at the two openings and the ratio of the areas of the openings. The magnitude of the inside pressure lies between P_1 and P_2 and is nearer the pressure at the greater area. The curve on page 8 is a plot of equation [12].

When there are three or more openings the inside pressure may be found by repeated trials. Equation [10] can be written

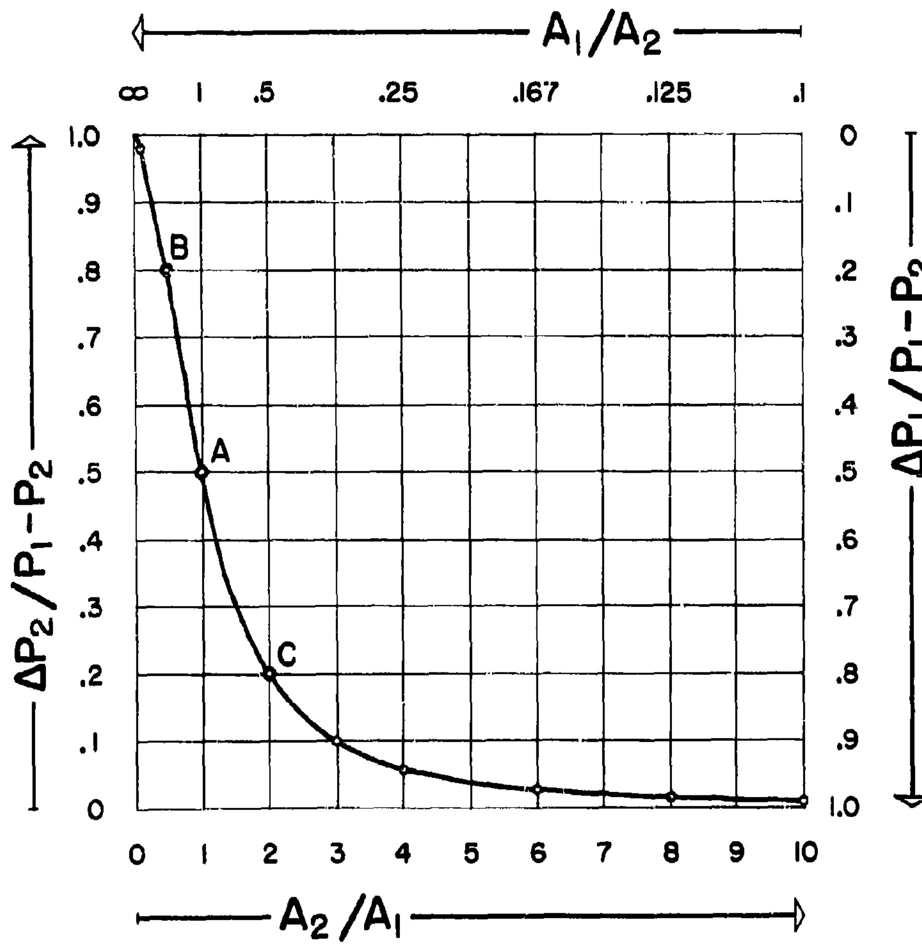
$$\sum (AV\rho)_{in} = \sum (AV\rho)_{out}$$

Solving with equation [6] for three openings where $P_2 < P_{in}$,

$$A_1 \rho_1 \sqrt{\frac{\Delta P_1}{C\rho_1}} = A_2 \rho_2 \sqrt{\frac{\Delta P_2}{C\rho_3}} + A_3 \rho_3 \sqrt{\frac{\Delta P_3}{C\rho_3}}$$

When the density is constant, this becomes

$$A_1 \sqrt{P_1 - P_{in}} = A_2 \sqrt{P_{in} - P_2} + A_3 \sqrt{P_{in} - P_3} \qquad [13]$$

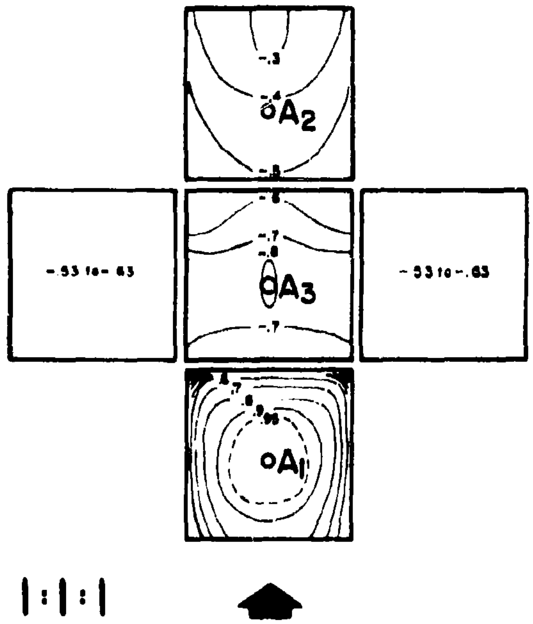


A1/A2
∞
1
.5
.25
.167
.125
.1
ΔP2/P1-P2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
B
A
C
ΔP1/P1-P2
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
0
1
2
3
4
5
6
7
8
9
10
A2/A1

Equation [13] can be solved for any one of the variables when the other six are known.

EXAMPLE:

$A_1 = A_2 = .5A_3$ (see Figure below)



$P_1 = 1.0$

$P_2 = -0.4$

$P_3 = -0.8$

where all pressures are in the same units.

Assuming $P_{in} = 0$ and using equation [13] ,

Flow in: $A_1\sqrt{P_1 - P_{in}} = A_1\sqrt{1 - (0)} = A_1$

Flow out: $A_2\sqrt{P_{in} - P_2} + A_3\sqrt{P_{in} - P_3} = A_1\sqrt{0 - (-.4)} + 2A_1\sqrt{0 - (-.8)}$

$= A_1 \; (2.420)$

$A_1 \; (1.000) \neq A_1 \; (2.420)$

Since there is more flow out than flow in, the assumed inside pressure is too high. For the second try let $P_{in} = -.4$. Then

$$\text{Flow in:} \quad A_1\sqrt{P_1 - P_{in}} = A_1\sqrt{1-(-.4)} = A_1\sqrt{1.4} = A_1\,(1.183)$$

$$\text{Flow out:} \quad A_3\sqrt{P_{in} - P_3} = 2A_1\sqrt{-.4-(-.8)} = 2A_1\sqrt{.4} = A_1\,(1.264)$$

$$A_1\,(1.183) \neq A_1\,(1.264)$$

Another trial indicates that the pressure inside the structure is between -.40 and -.41.

The above procedure is good for any number of openings.

The leakage through continuous surfaces such as walls, floors, and ceilings, as well as cracks at surface joints and windows, does not vary as the square root of the pressure drop under all conditions, but when the relationships between the pressure drop across the wall or crack and the air leakage rate per unit area are known the pressure inside a building can be solved for by the method illustrated for large cracks and openings. Since the pressure outside the structure varies from point to point, it is necessary to use several zones.

EXPERIMENTAL PROCEDURE

The wind tunnel used in this investigation was of the low velocity recirculating type. Air flow through the tunnel is induced by three 48-inch fans, each rated at 20,000 cubic feet per minute. Each fan is driven by a one horsepower d-c motor with an electronic variable speed control. The frontpiece is a general view of the tunnel.

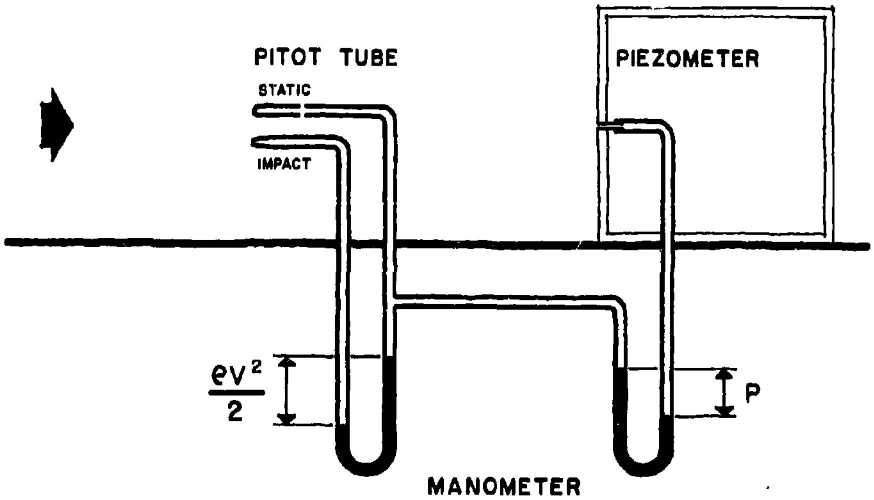
The models themselves were carefully constructed of plywood or sheet plastic (plexiglas). The block type models used for the air pattern investigations consisted of 4-by4-inch blocks with lengths of 4, 8, and 16 inches. The gabled and shed roofs had pitches of 1/12 to 12/12.

The models used for the pressure investigations were equipped with piezometer holes placed in only a few of the sides. The model elements were moved from position to position until complete pressure data for the entire structure were obtained.

Observations of the flow patterns were made by means of titanium tetrachloride smoke introduced into the air stream. Dimensions of the eddy currents were obtained by taking the average of several measurements for each model. Observations of the flow within the eddy were also made.

Impact pressure measurements in the undisturbed flow upstream of the model were made by means of a Pitot tube connected to a sensitive differential manometer or a strain gage transducer in conjunction with a recording oscillograph. Similar instruments were used to measure the pressures on the surfaces of the models.

The dimensionless coefficient, $\frac{P}{\rho V^2/2}$, was obtained by finding the ratio of the pressure reading when connected to the piezometer tube to the pressure reading when connected to the impact tube. It was not necessary to compute the value of the velocity or the density.



DIAGRAMMATIC SKETCH OF INSTRUMENTATION

ANALYSIS OF RESULTS

Air Patterns

The results for several block type buildings are shown in Appendix I. When the wind is normal to the building the general shape of the air pattern changes when the width to height ratio is changed. When the width to height ratio of the building is less than 1/2, the width of the building does not influence the downwind eddy (page 30). When the width to height ratio is greater than 2 the high velocity air stream strikes the roof and the stream flows horizontally along the roof. For this case the dimension of the downwind eddy (measured from the back of the building) is constant for all values of width to height ratios greater than 2. If the roof pitch is such that the high velocity air stream does not strike the roof, then the roof angle does not affect the downwind eddy. In all cases the downwind eddy dimension increases with an increase of the building length.

The diagrams on pages 31 and 32 show how air flow around four basic building shapes is affected by changes in orientation.

Pressure Distribution

Dimensionless pressure coefficients are reproduced in Appendix II. These contour plots are good for any air density, wind speed, and prototype scale. The diagram on page 39 is a contour plot for an army squad tent. The air patterns and pressure distribution at the midsection of long block type structures are shown on pages 40 thru 47. Impact pressures, $\frac{\rho V^2}{2}$, for various wind speeds are given in Table 1.

The pressure contours and Table 1 can be used to find the pressure at any point on a building. Assume for illustration that it is desired to

TABLE NO. 1

IMPACT PRESSURES FOR VARIOUS WIND SPEEDS

VELOCITY			IMPACT PRESSURE = $\frac{\rho V^2}{2}$		
MILES PER HR.	FEET PER SEC.	FEET PER MIN.	POUNDS PER SQUARE FT.	POUNDS PER SQUARE IN.	INCHES OF WATER
5	7.33	440	0.0627	0.000435	0.0121
10	14.66	880	0.250	0.00174	0.0482
12	17.60	1056	0.361	0.00251	0.0700
15	22.00	1320	0.564	0.00392	0.1084
20	29.33	1760	1.002	0.00695	0.193
25	36.66	2200	1.566	0.01086	0.301
30	44.00	2640	2.260	0.0156	0.434
35	51.33	3080	3.070	0.0213	0.590
40	58.66	3520	4.010	0.0278	0.771
45	66.00	3960	5.070	0.0352	0.976
50	73.33	4400	6.270	0.0435	1.205
55	80.66	4840	7.580	0.0526	1.458
60	88.00	5280	9.020	0.0626	1.735

The data in the above table are for a standard air density of 0.075 lb. per cu. ft. At sea level (29.92 inches of Hg. barometric pressure) this is equivalent to dry air at 70° F.

know the pressure at the center of a 20-by-40-foot face of a 20-by-20-by-40-foot building when the wind speed is 40 miles per hour at 70° F and is parallel to the 20-by-40-foot face. From the diagram on page 36 the value of $\frac{P}{\rho V^2/2}$ is -.6. The value of $\rho V^2/2$ is found from Table 1 to be 0.0278 pounds per square inch or 0.771 inches of water. The prototype pressure will then be

$$P = \left[\frac{P}{\rho V^2/2}\right]\left[\frac{\rho V^2}{2}\right]$$

$$= (-.6)\ (0.0278) = -0.01668 \text{ pounds per square inch, or}$$

$$= (-.6)\ (0.771) = -0.4626 \text{ inches of water}$$

where the negative sign denotes a pressure below atmospheric. The nomograph reproduced on page 48 will also give the above pressures.

Influence of Obstructions on Pressure Distribution

The plot on page 50 shows the influence of obstructions on the magnitude of the pressures on three sides of a building. The instantaneous values for several conditions are shown on the oscillograph charts on pages 51 thru 53 in Appendix III. These charts show the gustiness on the leeward side of the building. This indicates that very little turbulence is added by the building to that imposed by another building or other local obstructions.

The variations in pressure shown on the oscillograph charts are the results of mechanical turbulence. Thus, the building and other obstructions in rough country give rise to gustiness, and while over level country and over the sea mechanical turbulence is at a minimum. It follows that if the obstructions in the neighborhood of a building vary with direction, the gustiness will vary with wind direction.

Army squad tents were also used to study the effect of adjacent tents on the pressure at the surface of the several tents in the group. The pressure was measured at a midsection of the tents.

The arrangements tested with a description of the general effects are as follows:

1. Squad tent with squad tent on windward side.

On page 54 the value of the dimensionless pressure ratio $\frac{p}{\rho V /2}$ plotted opposite the point to which it refers on the cross-section. Curves for five values of A/L are shown. On page 55 the pressure ratio is plotted against the geometric ratio A/L. The pressures at six points on the tents are shown. It will be seen as the shielding tent approaches from infinity (fully exposed condition) the pressure on the windward wall is gradually reduced and becomes zero when the distance between them is 1 1/2 times the width of the tent. For an A/L less than 1 1/2 the pressures are negative and all the windward surfaces are in the turbulent region behind the shielding tent. The pressures on the windward roof are reduced as A/L is reduced. At A/L below 2 the pressure is negative at all points on the windward roof. The pressure is negative for all values of A/L at points near the ridge. On the leeward roof and wall the pressure is negative for all values of A/L, and approach zero as A/L is reduced.

2. Three squad tents in line.

The diagrams on pages 56 and 57 show the pressure ratio at the center cross-section for each of three tents. The ratio of A/L is 1 in the diagram on page 56 and 2 in the diagram on page 57. The pressure ratio decreases on the windward wall and roof for both shielded tents as A/L

is decreased. The pressure ratios on the leeward walls and roofs are negative in all cases. These ratios are approximately the same for A/L of 1 and A/L of 2.

3. Pair of squad tents on windward side.

The figures on pages 58 and 59 show that the pressure ratios are not affected by the number of lines of tents. This is shown by the diagrams on pages 54 and 58 when A/L = 1, and pages 54 and 59 when A/L = 2.

4. Squad tents with two tents equidistant on windward side with a gap of one tent length.

As shown by the diagram on page 60, the pressure ratio changed very little for A/L ratios of unity to the fully exposed condition.

Entrances to Underground Shelters

1. Fully exposed condition.

Tests were first carried out with the underground shelter entrance on an open plane. In this situation the pressure is negative (below atmospheric) at all points except on the leeward side at the upper edge. The dimensionless ratio $\frac{P}{\rho V^2/2}$ is near -0.05 for all surfaces except the upper edge, where the ratio is zero (atmospheric pressure).

2. Shielded conditions.

The results of shielding with vertical walls are given on pages 62 and 63. When the interference is on the windward side of the entrance, the air pattern is seen to fall into three zones. Two of these zones are affected by the interference. The low pressure eddy zone is nearest the wall, where the dimensionless pressure ratio $\frac{P}{\rho V^2/2}$ is -0.45. This zone extends to seven wall heights (L/h = 7) behind the wall. The transition low pressure zone

extends from seven to seventeen wall heights. The pressure ratio changes from -0.45 to -0.05 in this zone. When the entrance is more than seventeen wall heights from the wall the pressure ratio is the same as that for the fully exposed condition, indicating that the wall has no effect beyond this distance.

There are two zones when the wall is on the leeward side of the shelter entrance. The undisturbed zone extends beyond a distance of twelve wall heights, and the pressure ratio $\frac{P}{\rho V^2/2}$ is -0.05. In the high pressure zone the pressure ratio changes from -0.05 at L/h = 12 to 0.3 at L/h = 2.

When a stack (chimney) is placed above the entrance the pressures are reduced below the values for undisturbed conditions. The dimensionless plot on page 64 shows the pressure ratio versus the height/diameter ratio. For heights of more than one diameter the pressure ratio is -0.75.

In any case involving an underground shelter entrance in combination with an object which imposes wind interference, the pressure in the entrance will be below atmospheric pressure, with one exception. The pressure will become positive when the entrance is on the windward side of the interference. This positive pressure zone extends to a distance eleven times the height of the wall.

The pressure inside an underground shelter entrance closely approximates the pressure at that point of the interference zone in which the entrance is located. For example, the pressure ratio at the center of the leeward wall of a 1:1:5 structure is -0.5, and the pressure ratio in a shelter entrance located within seven wall heights of an interfering wall is -0.45.

When a stack is placed above the entrance, the pressures inside are those that exist on the roof of a block type structure. The pressure ratio on the roof of a 1:1:1 and a 1:1:2 block type structure is between -0.7 and -0.8, while the pressure ratio in an entrance with a stack is -0.75 when the stack height is more than one stack diameter.

Pressure Inside Building

The curves on page 66 show the inside pressure for several area ratios with a given set of pressures outside the structure. The photographs on pages 67 to 70 are designated by the letters A thru G. The same designation is used on the curves on pages 8 and 66. All measured pressures were consistent with the pressures calculated by the theoretical considerations. The following conclusions can be made from the experimental results as well as the theoretical considerations:

1. The sum of the flow into a structure is equal to the sum of the flow out.

2. The pressure inside the structure depends on:

   a. the pressures outside the building at the openings, which in turn depend on:

      (1) the geometry of the structure

      (2) the velocity of the wind

      (3) the density of the air

      (4) the orientation of the structure

   b. the area of the opening

3. The pressure inside the structure when three or more openings exist may be found by the repeated trial method.

B I B L I O G R A P H Y

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A P P E N D I C E S

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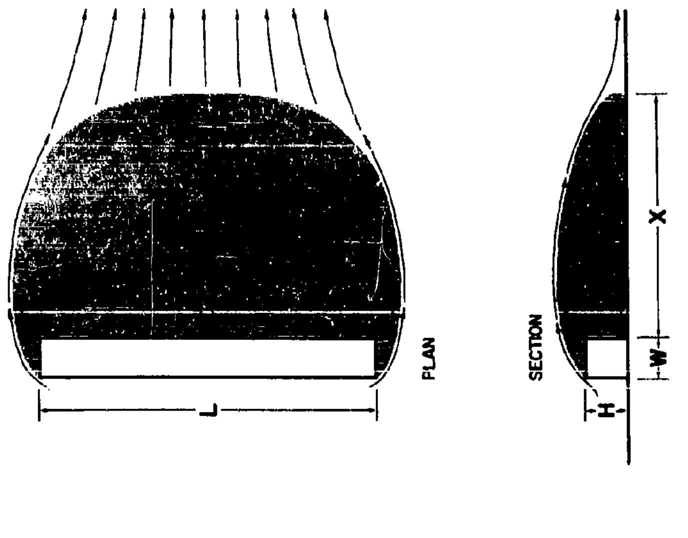
APPENDIX I

AIR PATTERNS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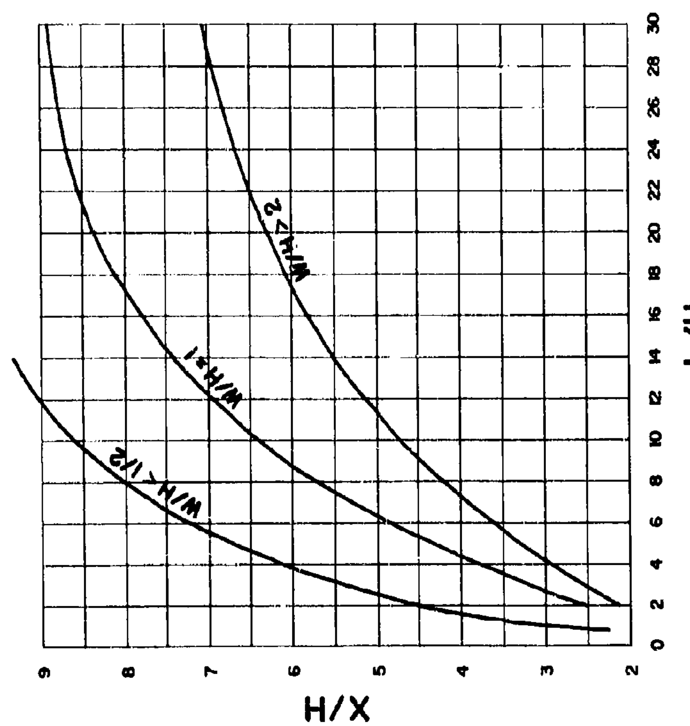
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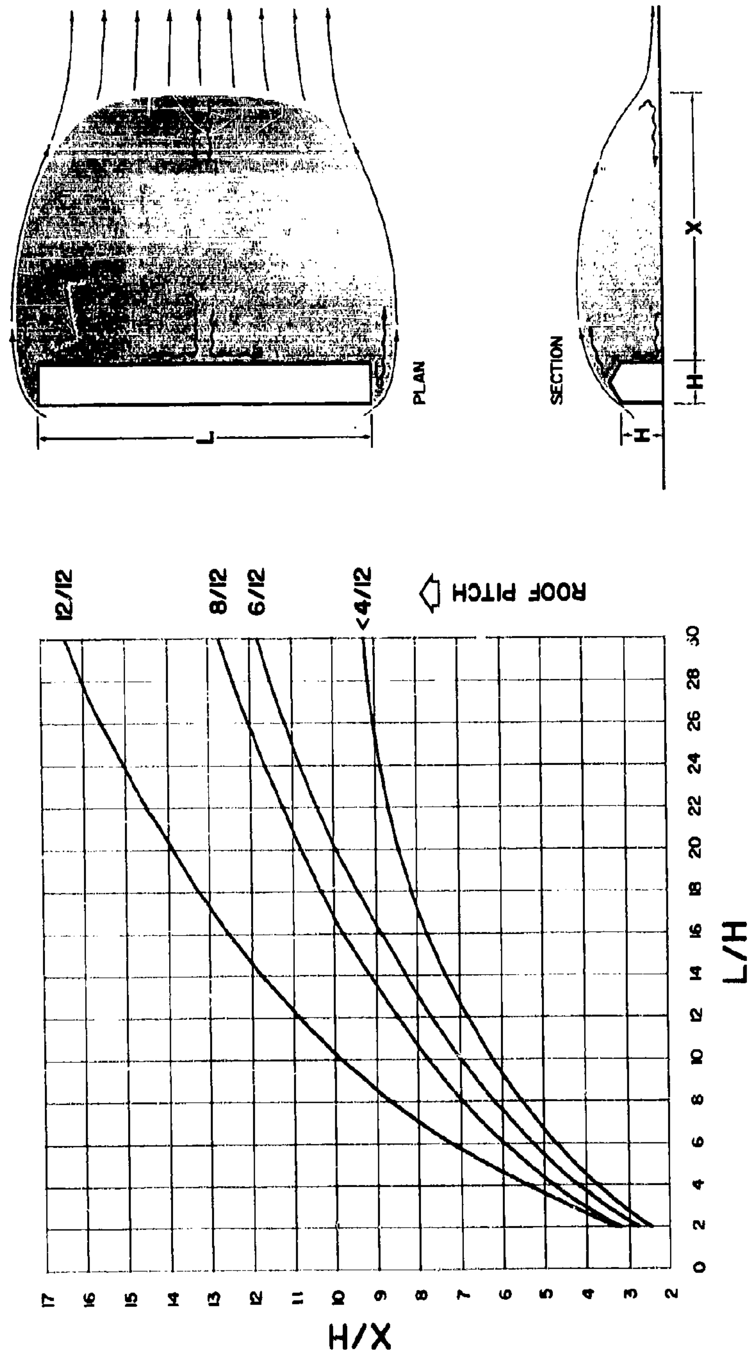
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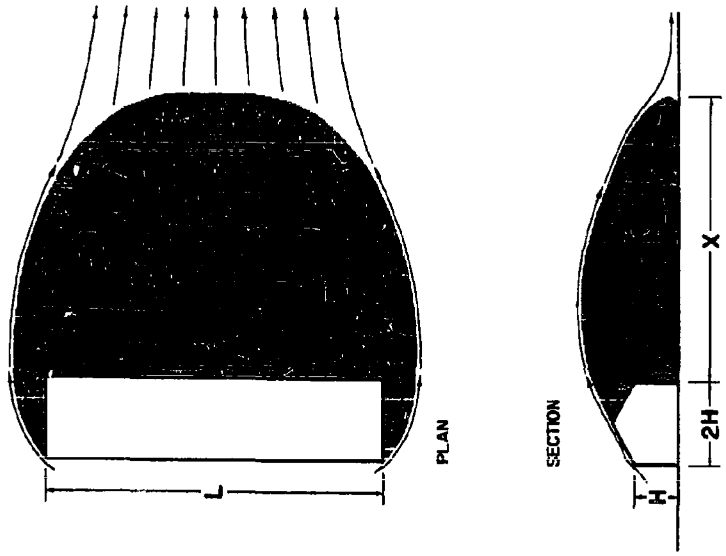
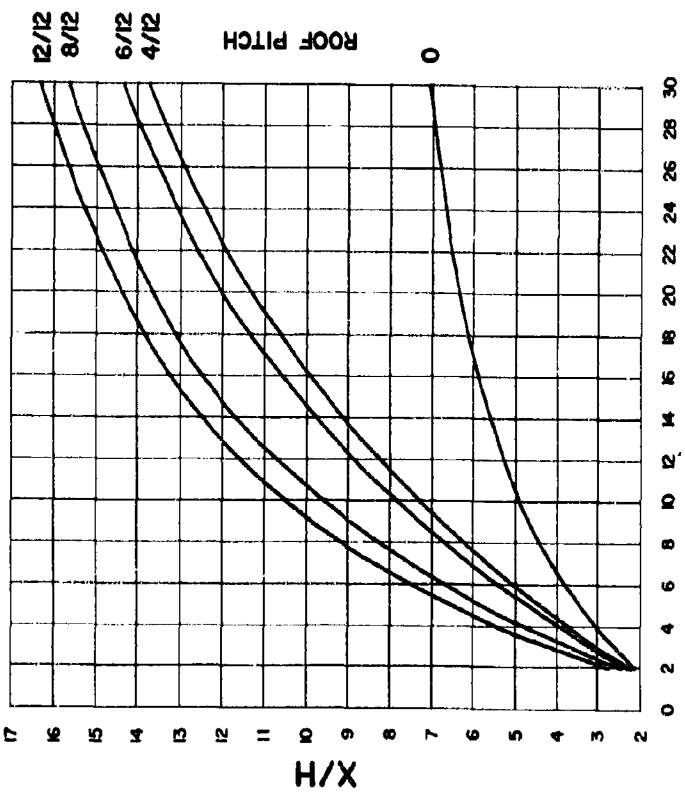
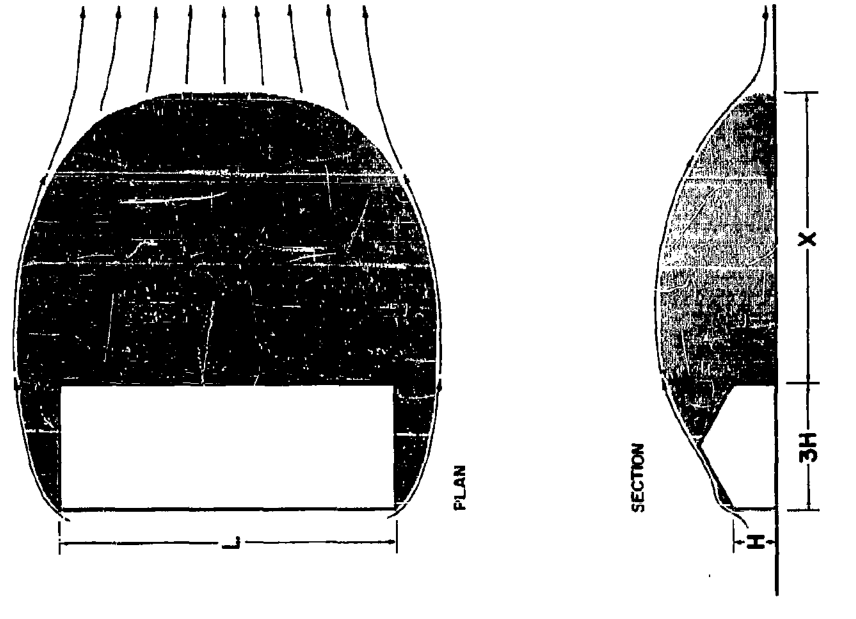
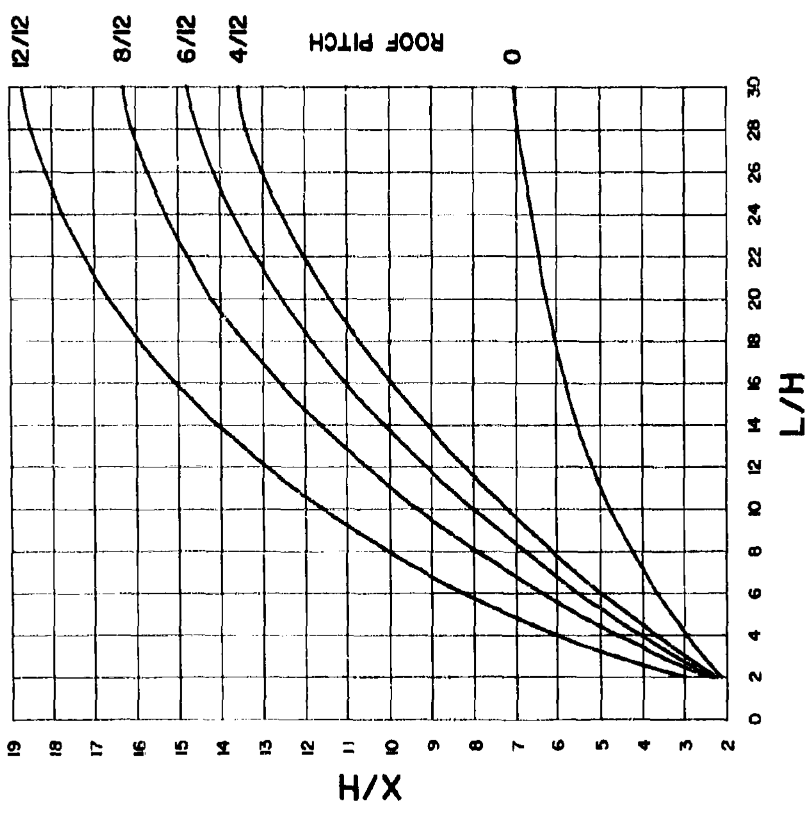
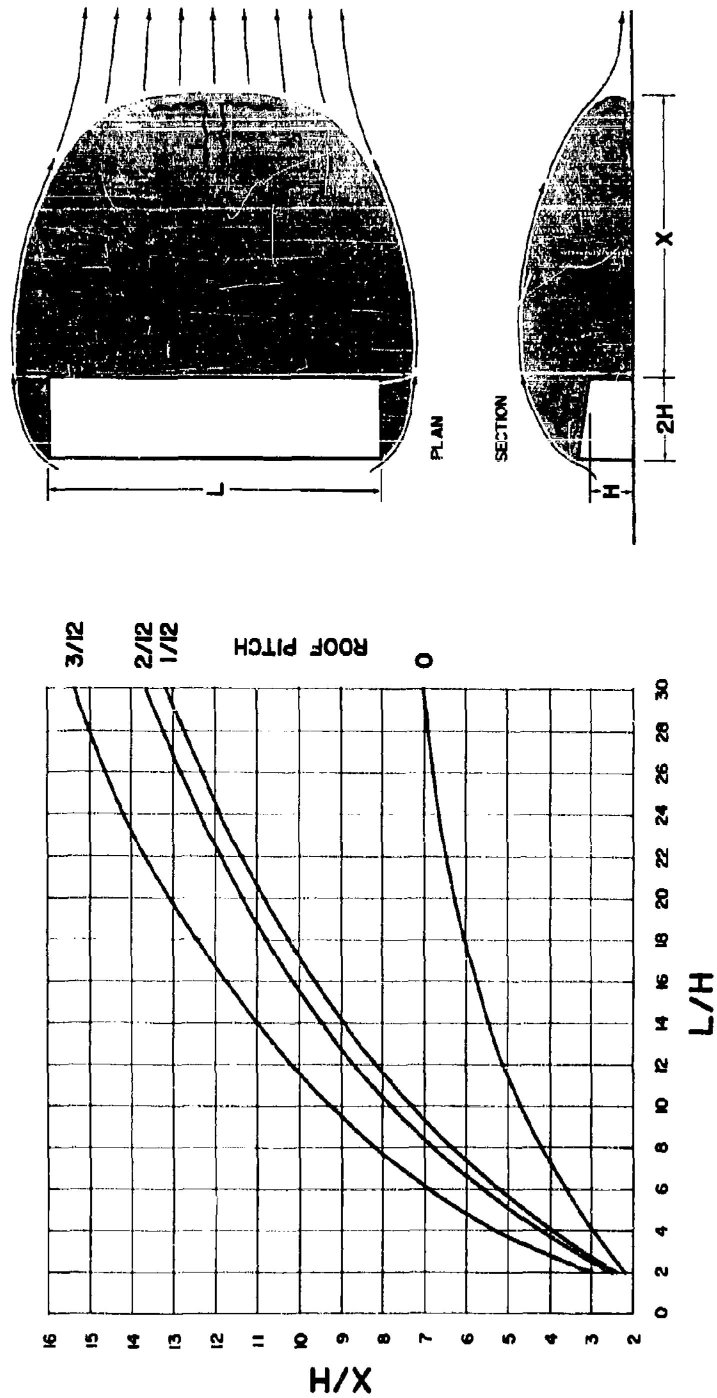
L/H


L
PLAN
SECTION
H
2H
X

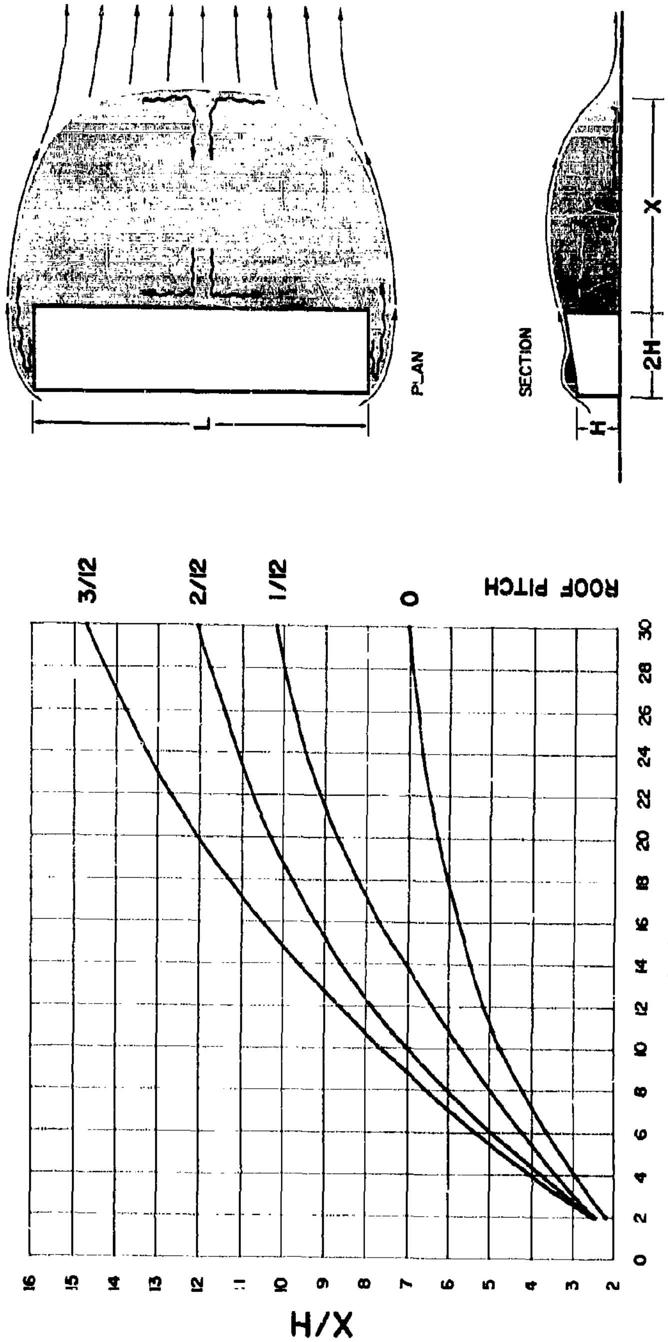

ROOF PITCH
12/12
8/12
6/12
4/12
0
L/H
X/H

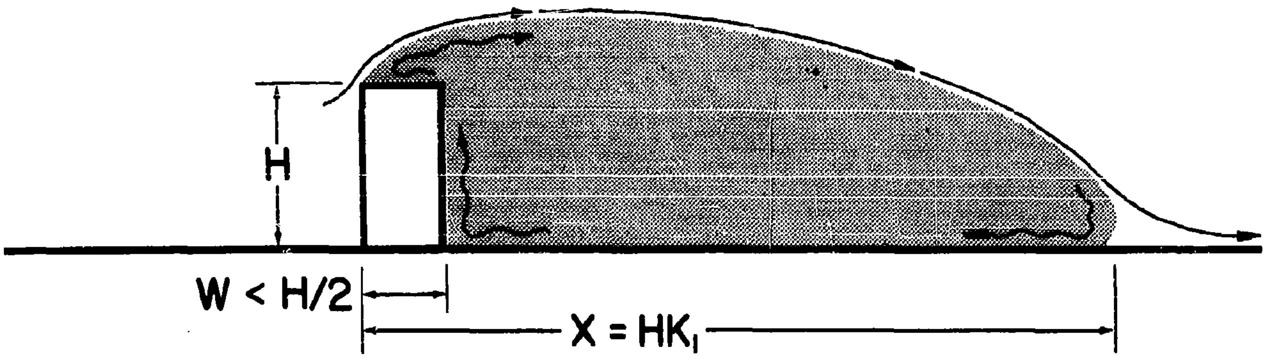

PLAN
SECTION
L
H
3H
X


ROOF PITCH
12/12
8/12
6/12
4/12
0
X/H
L/H

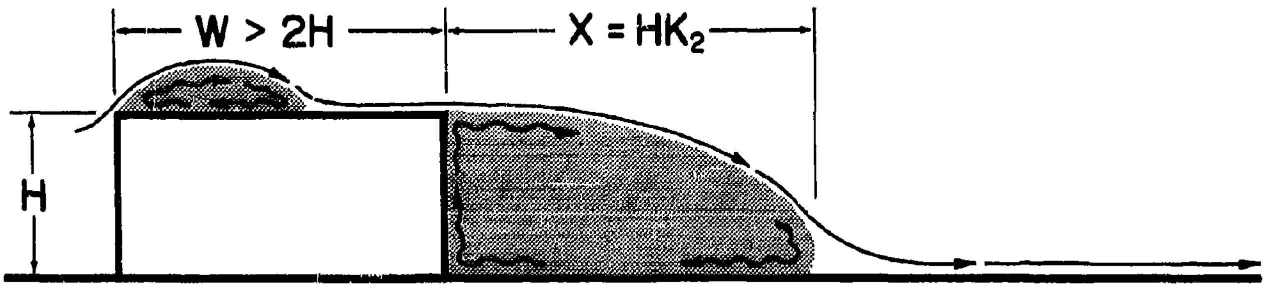


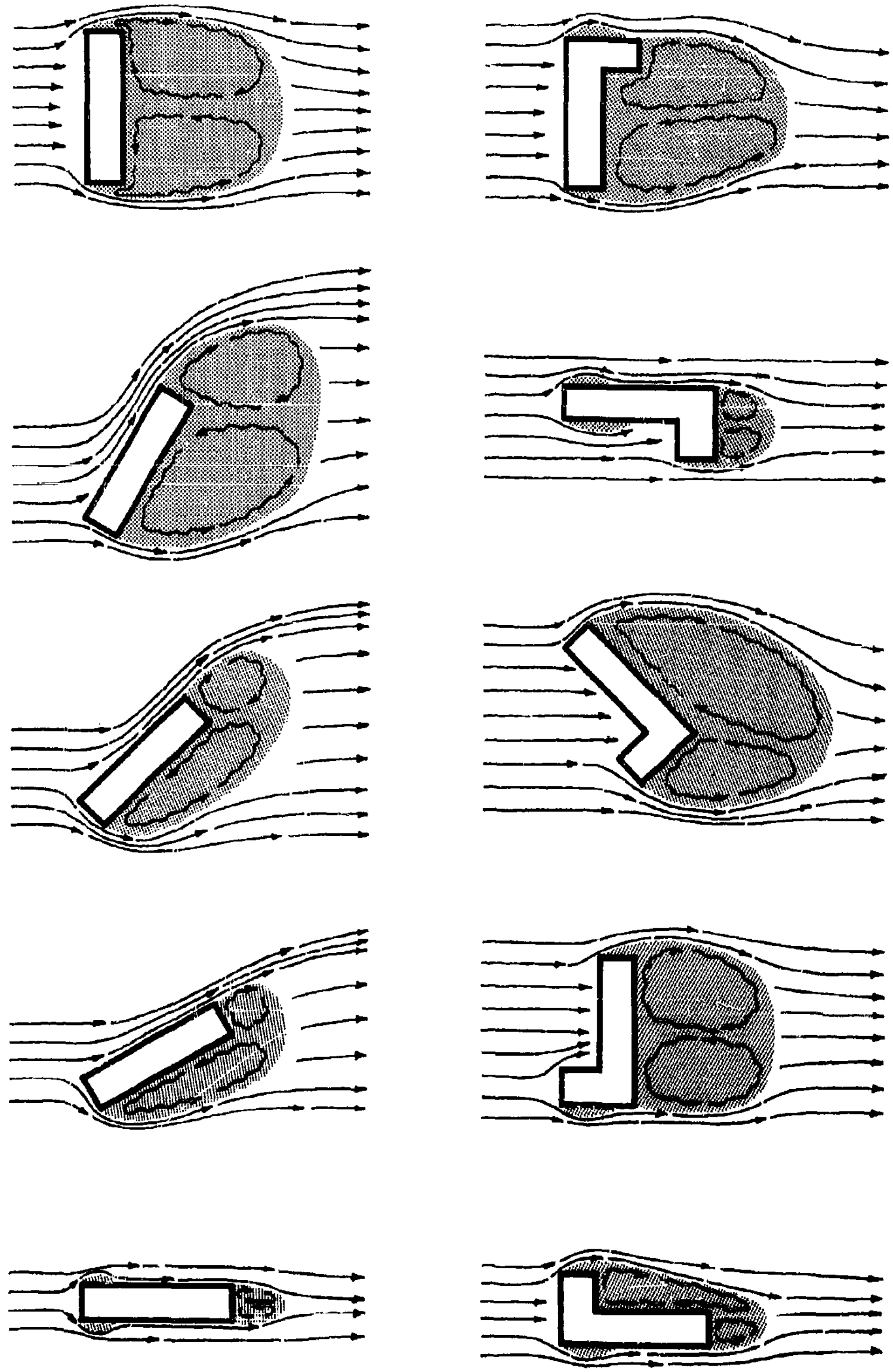
L
PLAN
SECTION
H
2H
X
ROOF PITCH
3/12
2/12
1/12
0
X/H
L/H

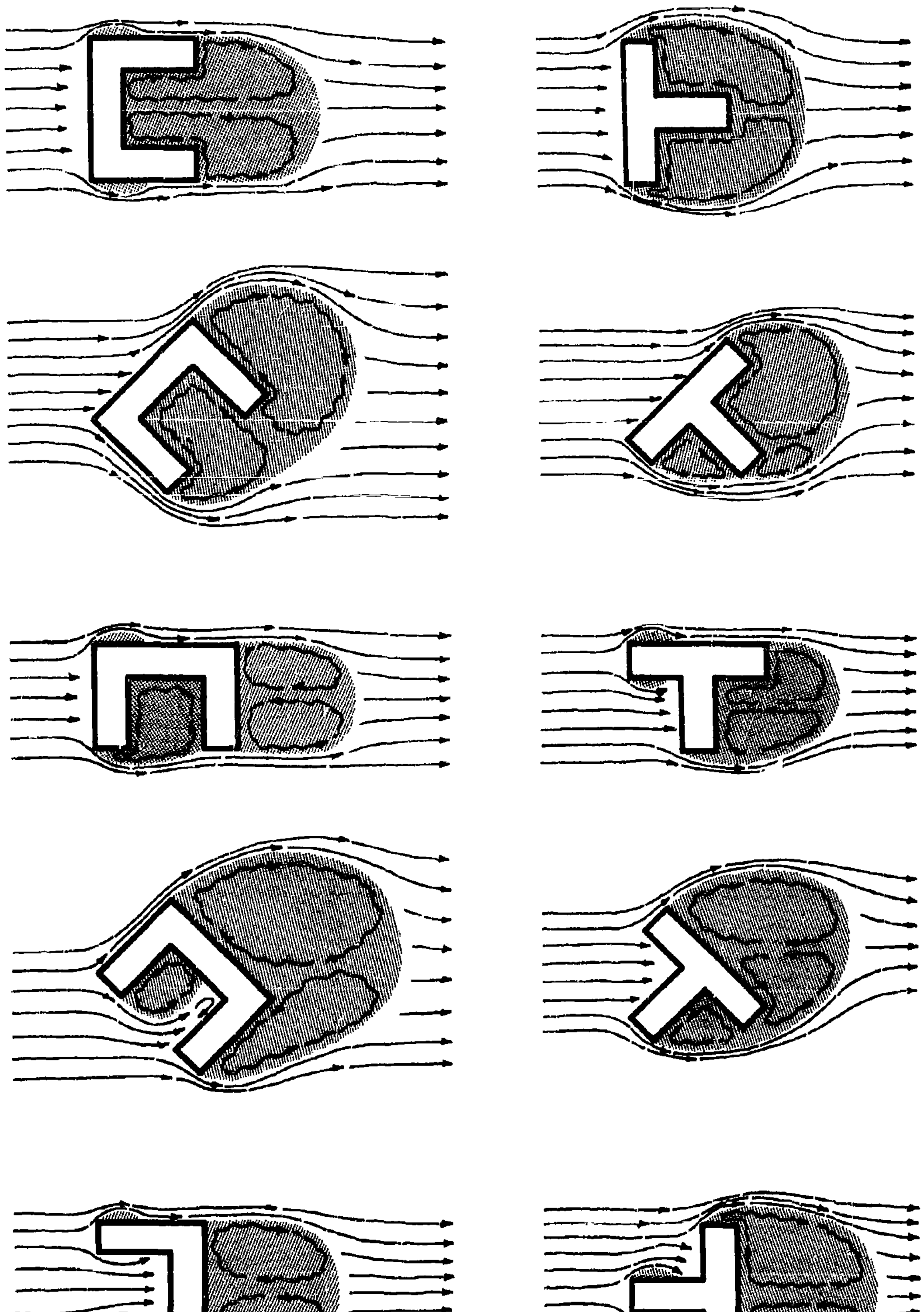

PLAN
SECTION
L
H
2H
X
ROOF PITCH
3/12
2/12
1/12
0
L/H
X/H



K1 AND K2 INCREASE AS THE LENGTHS OF THE BUILDINGS INCREASE

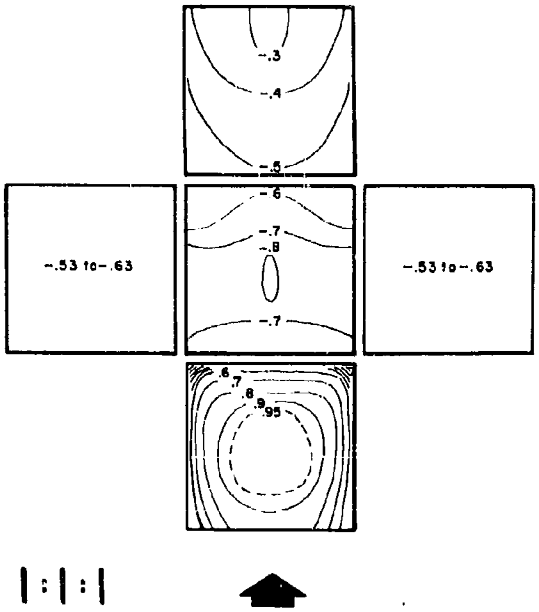




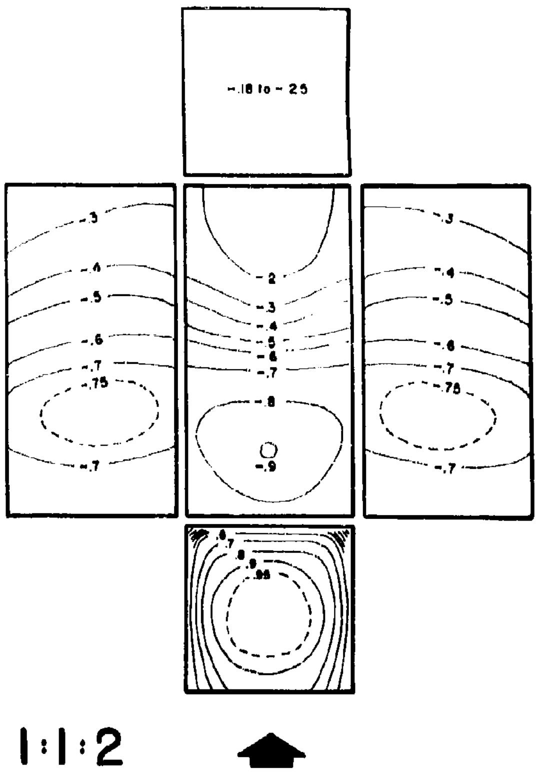


APPENDIX II

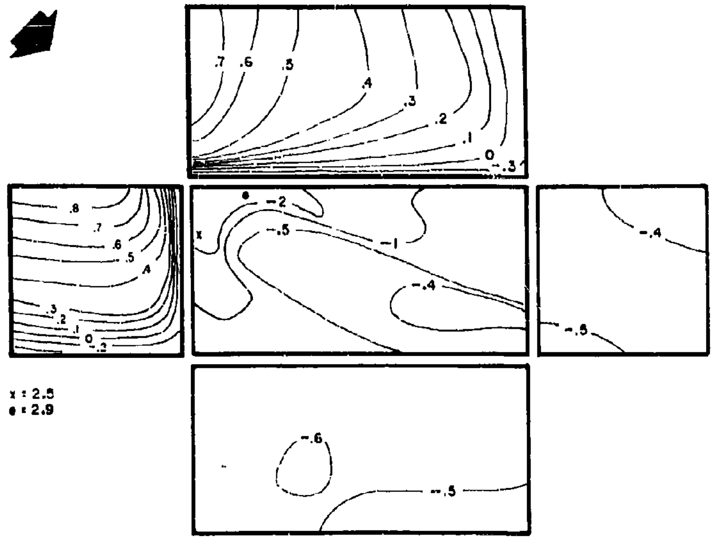
PRESSURE DISTRIBUTION ON FULLY EXPOSED MODELS


-.3
-.4
-.5
-.6
-.7
-.8
-.7
-.53 to -.63
-.53 to -.63
.6
.7
.8
.9
.95

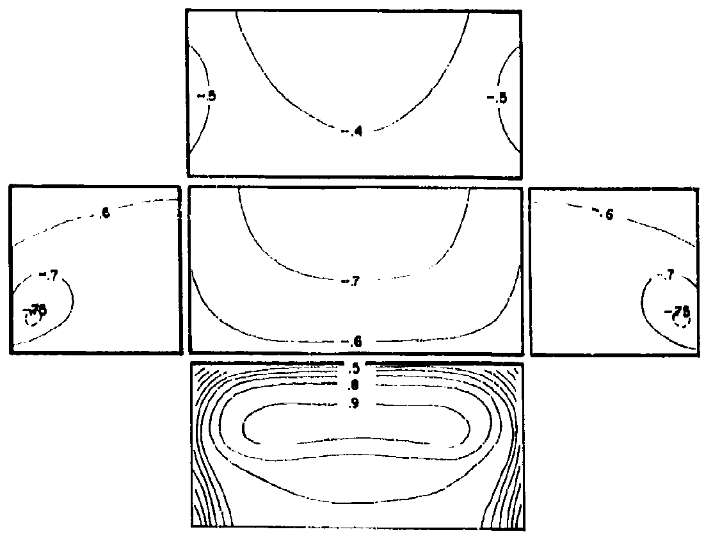
1:1:1


-.18 to -.25
-.3
-.4
-.5
-.6
-.7
-.75
-.7
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-.3
-.4
-.5
-.6
-.7
-.75
-.7
.6
.7
.8
.9
.95

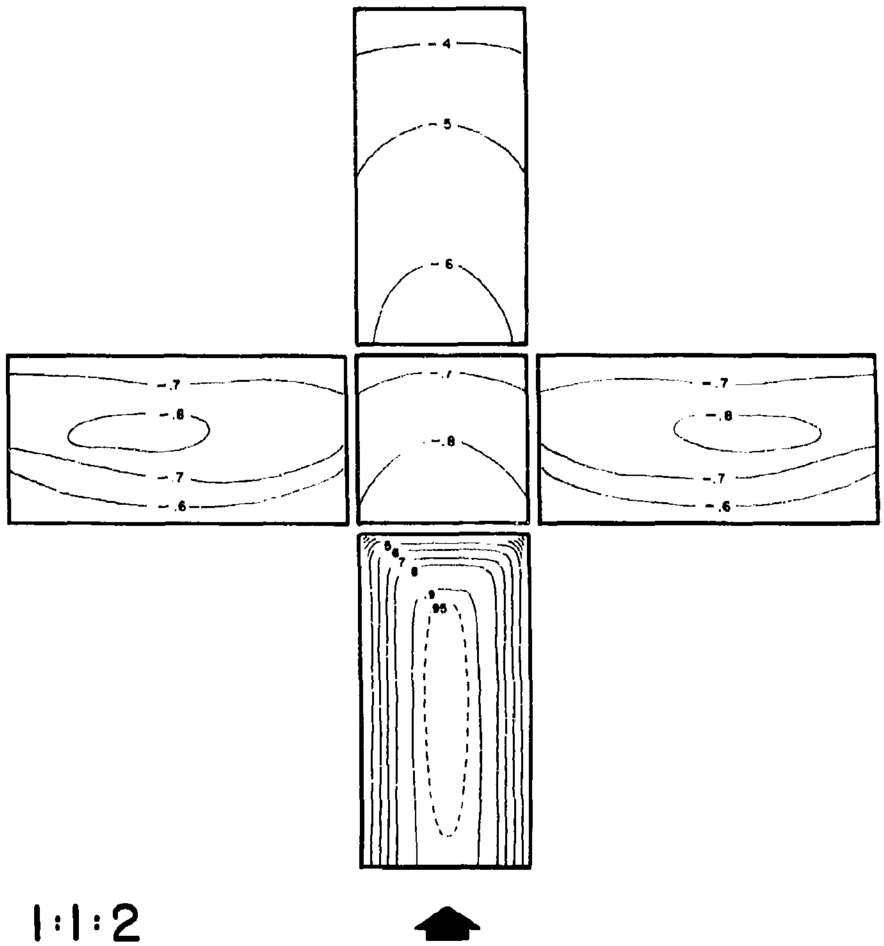
1:1:2



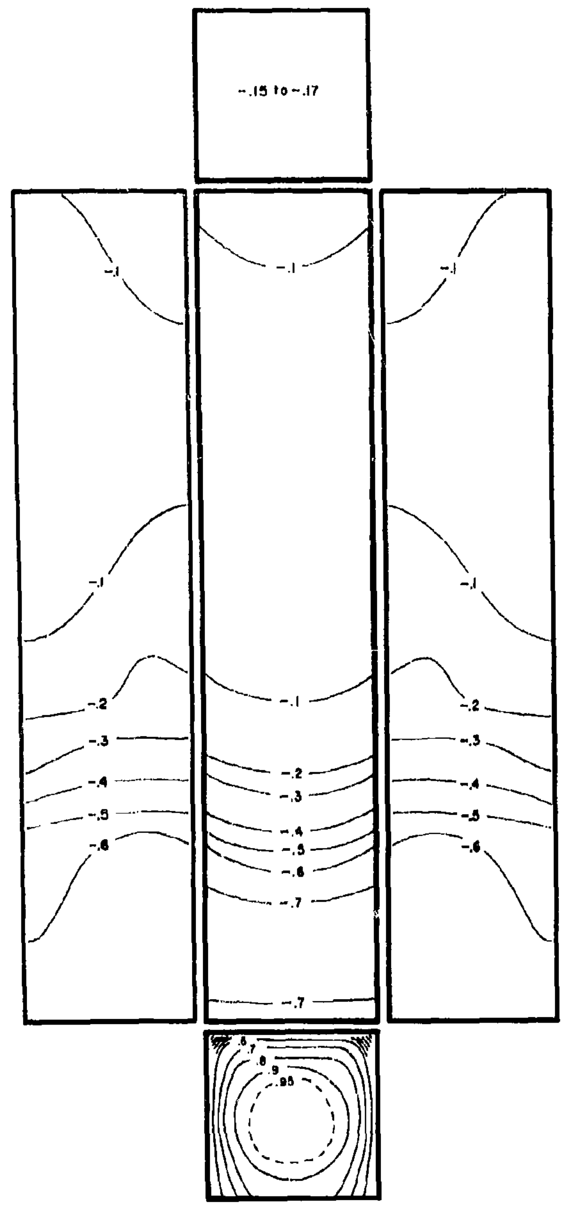
1:1:2



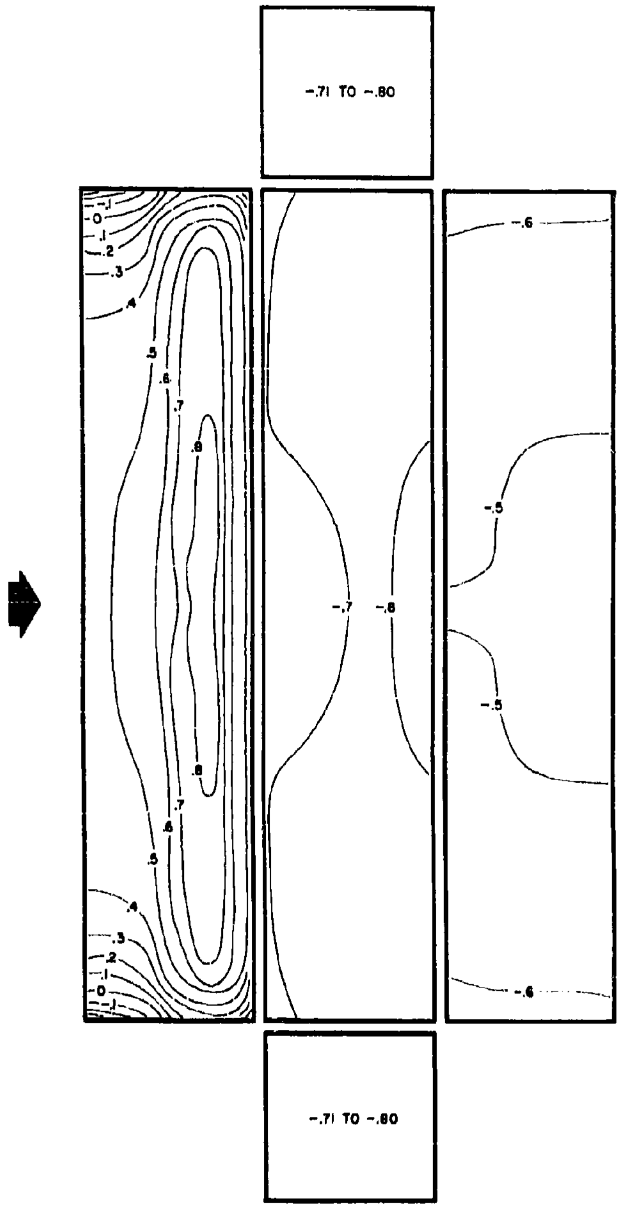
1:1:2



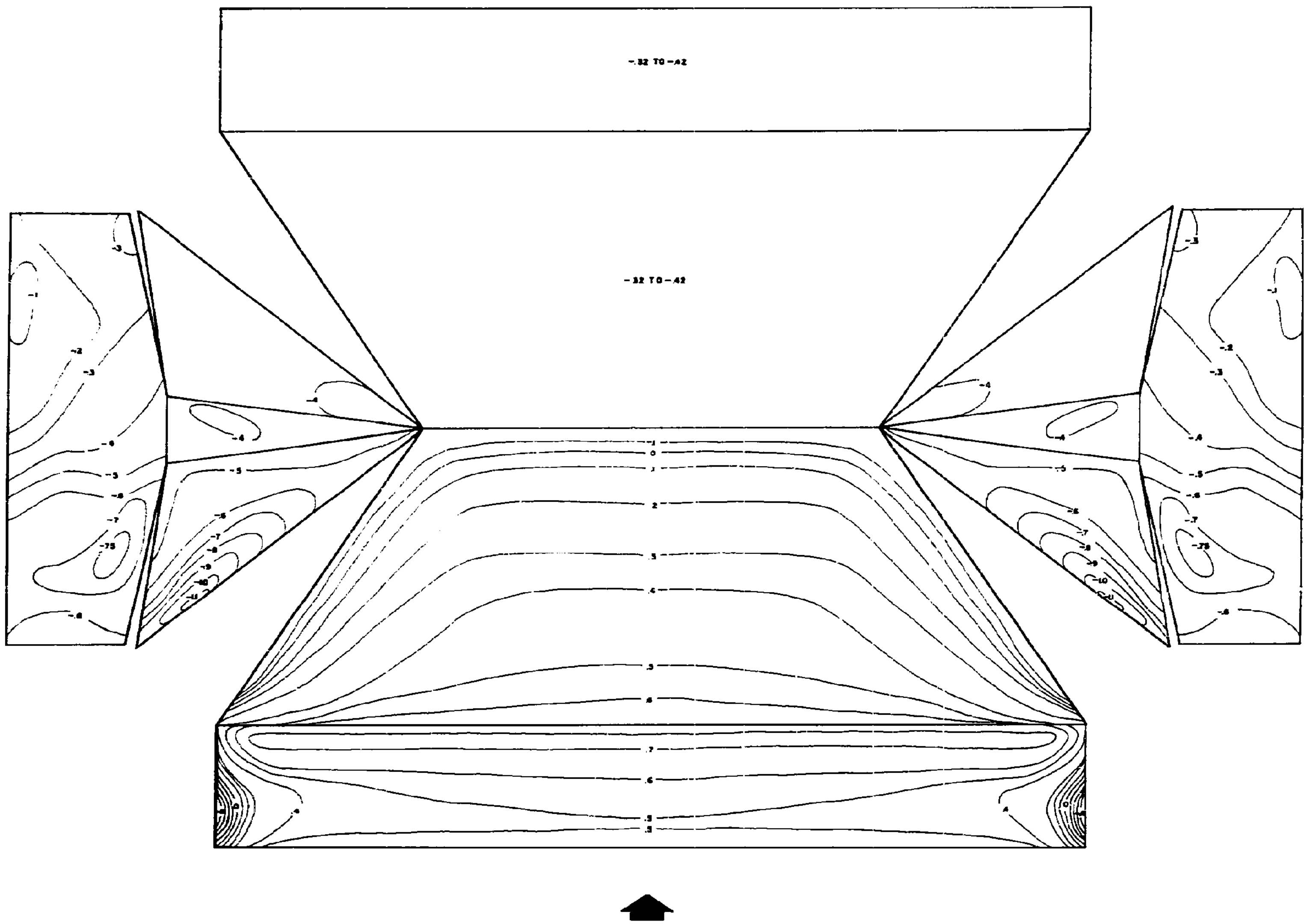
1:1:2



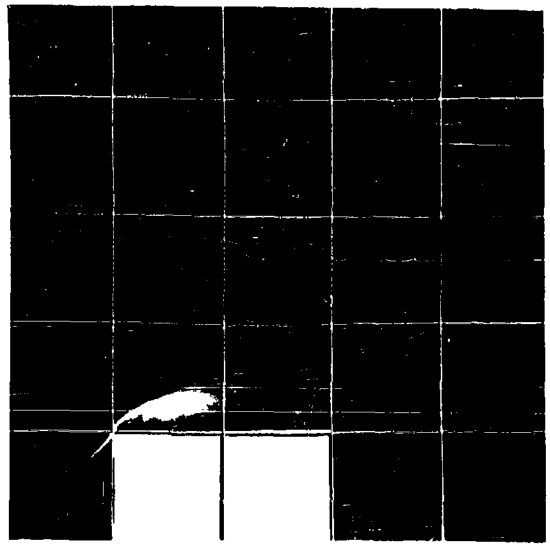
1:1:5

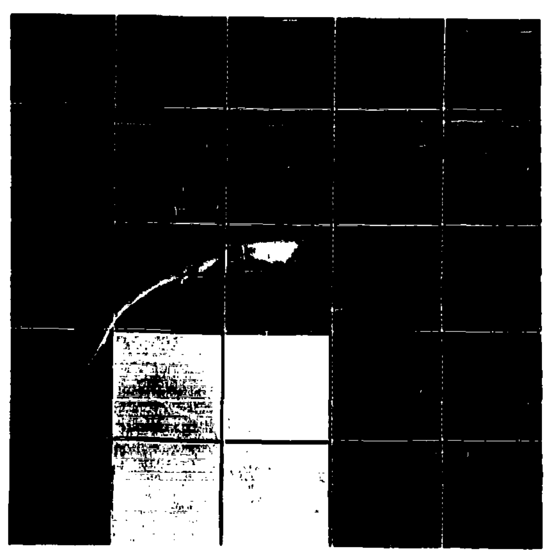


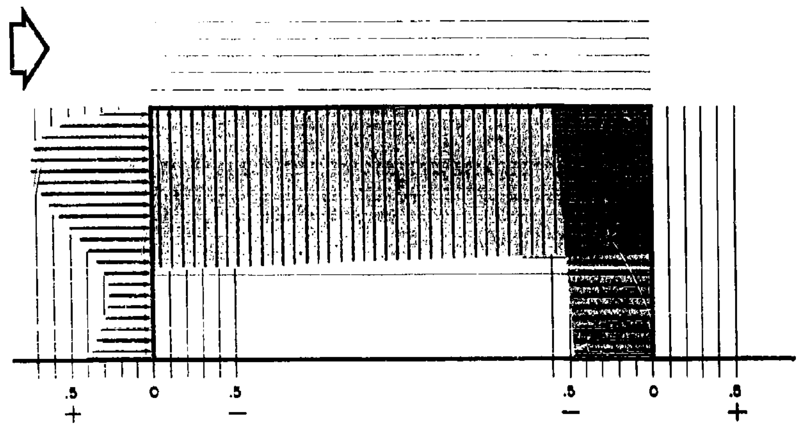
1:1:5



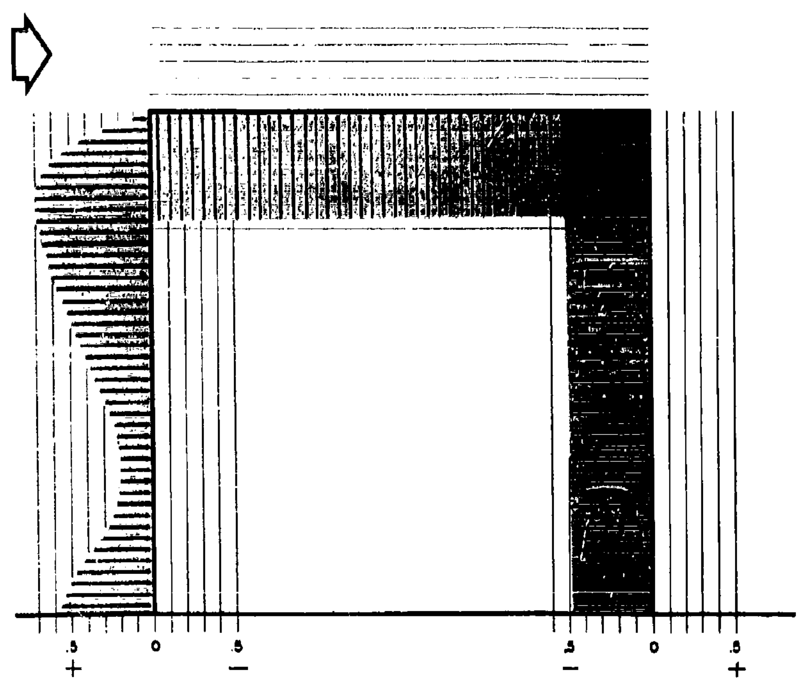
DISTRIBUTION OF PRESSURE ON U.S. ARMY SQUAD TENTS



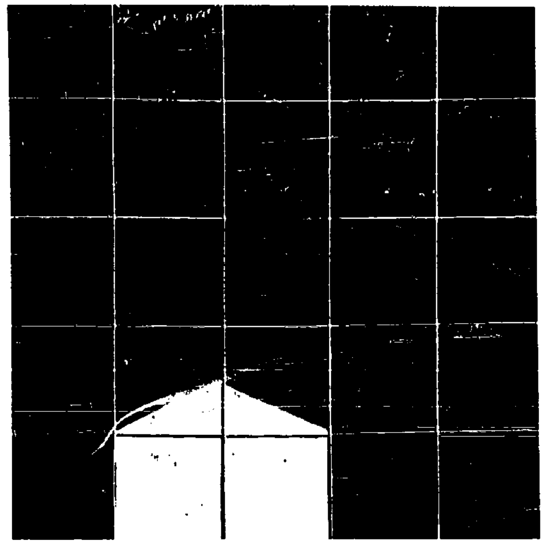


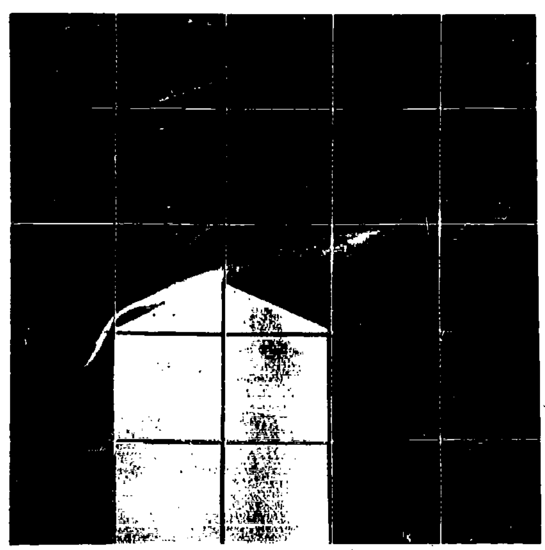


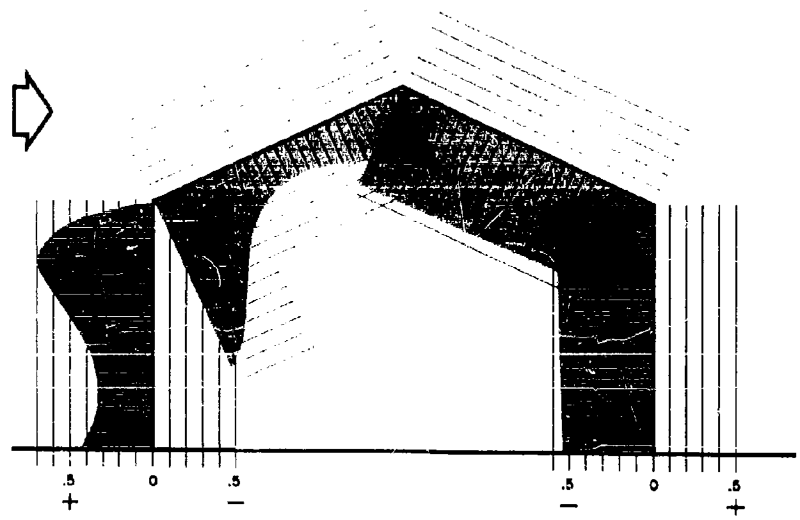
H/W = 1/2   Θ = 0°



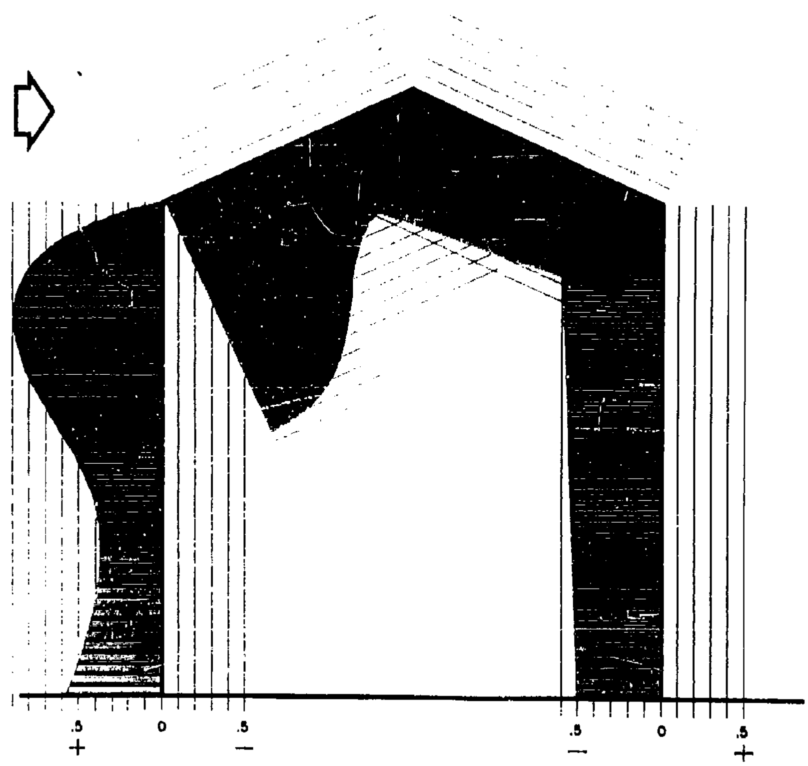
H/W = 1   Θ = 0°



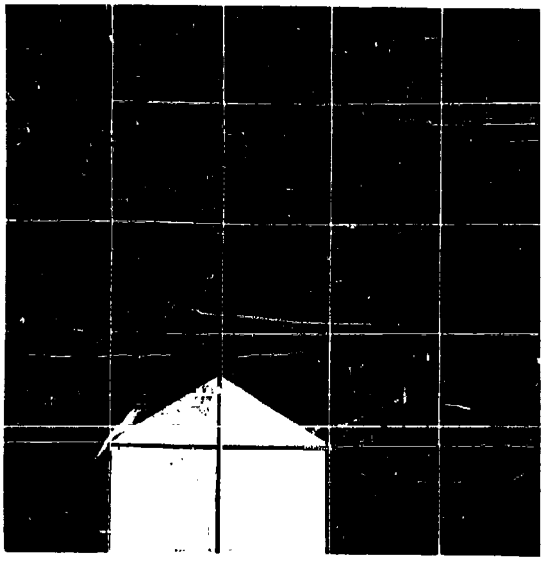


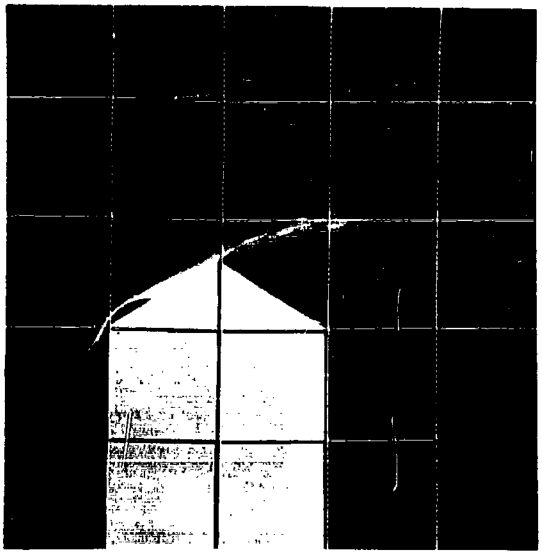


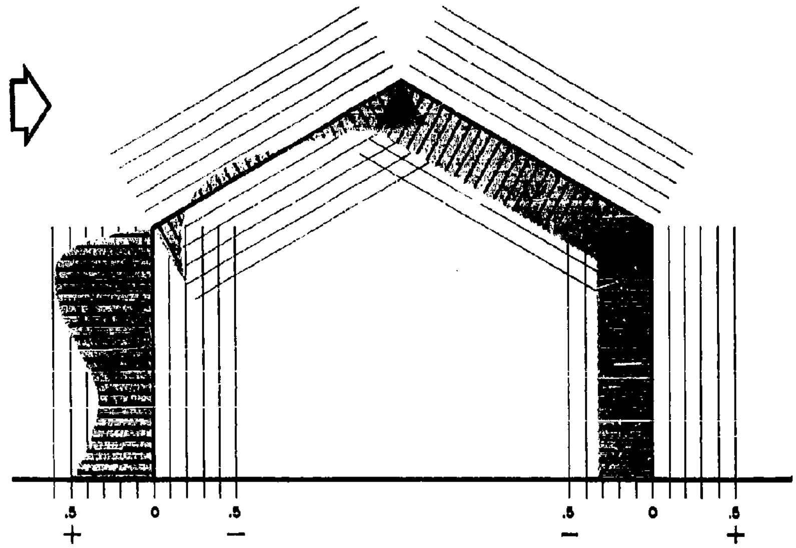
H/W = 1/2 θ = 25°



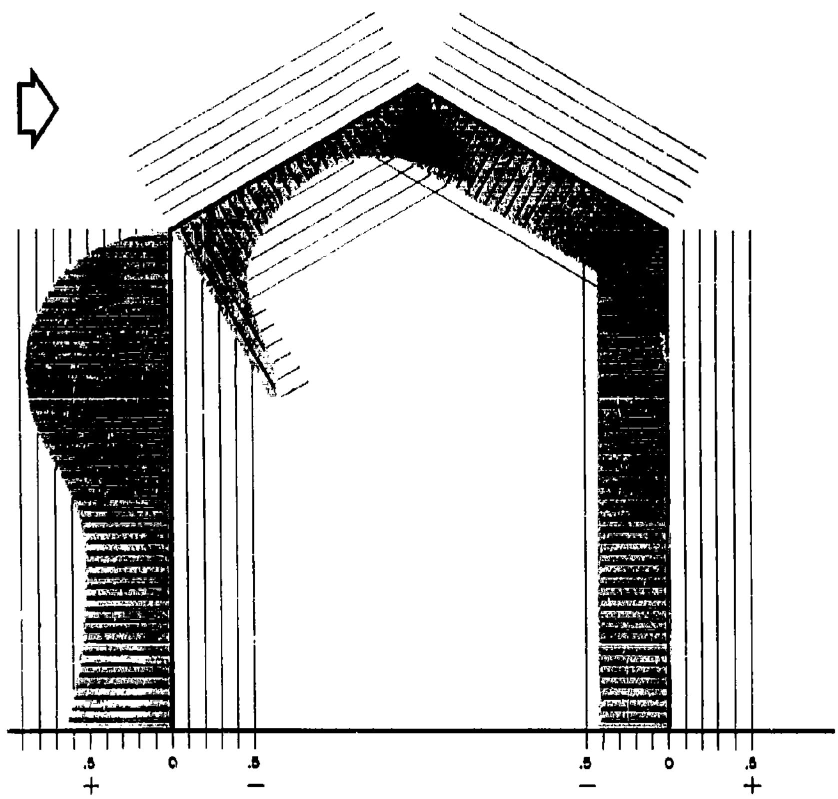
H/W = 1 θ = 25°



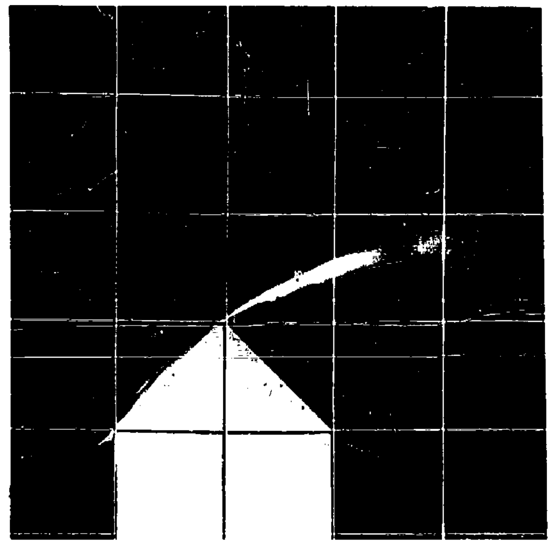


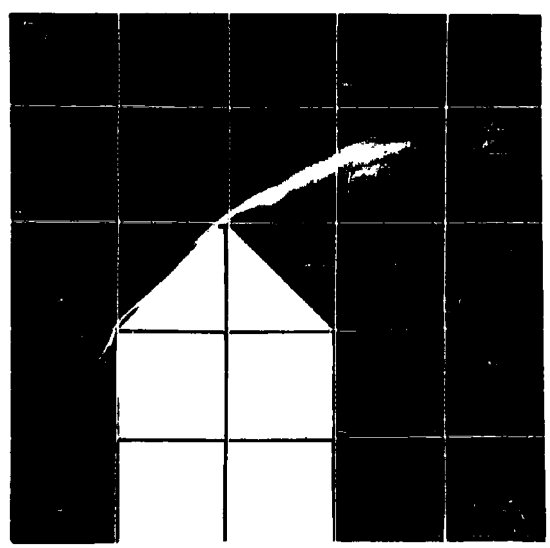


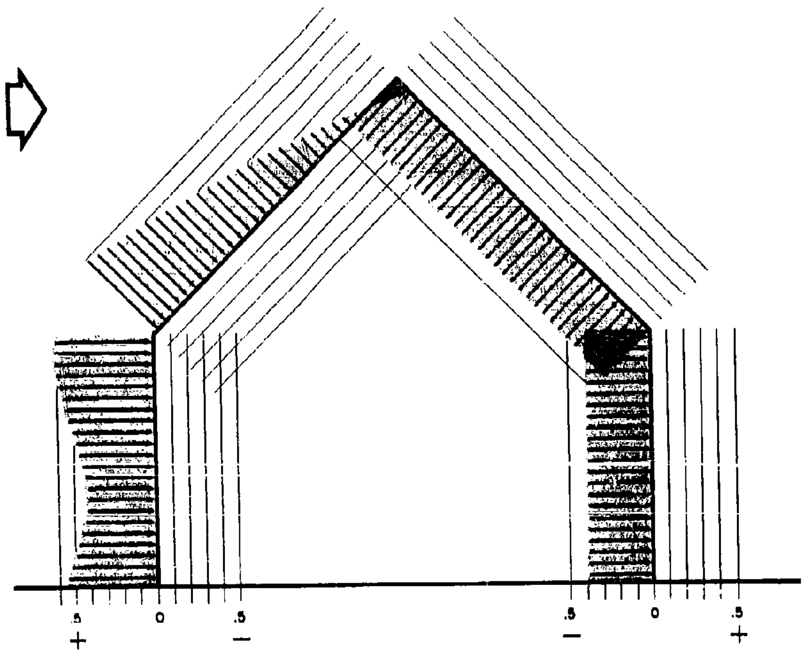
H/W = 1/2 θ = 30°



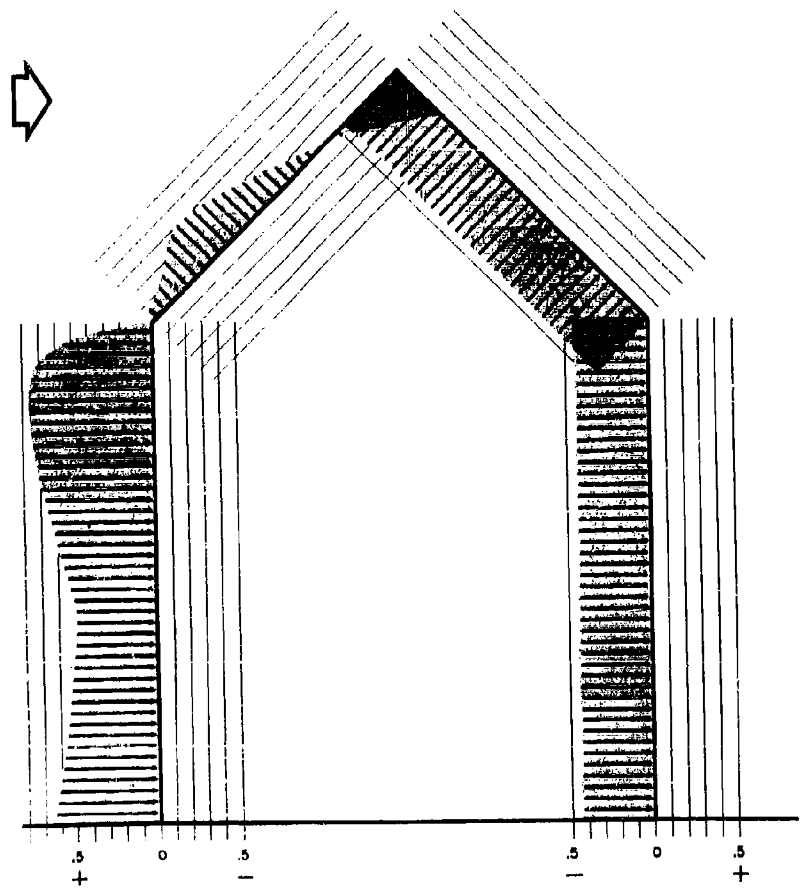
H/W = 1 θ = 30°



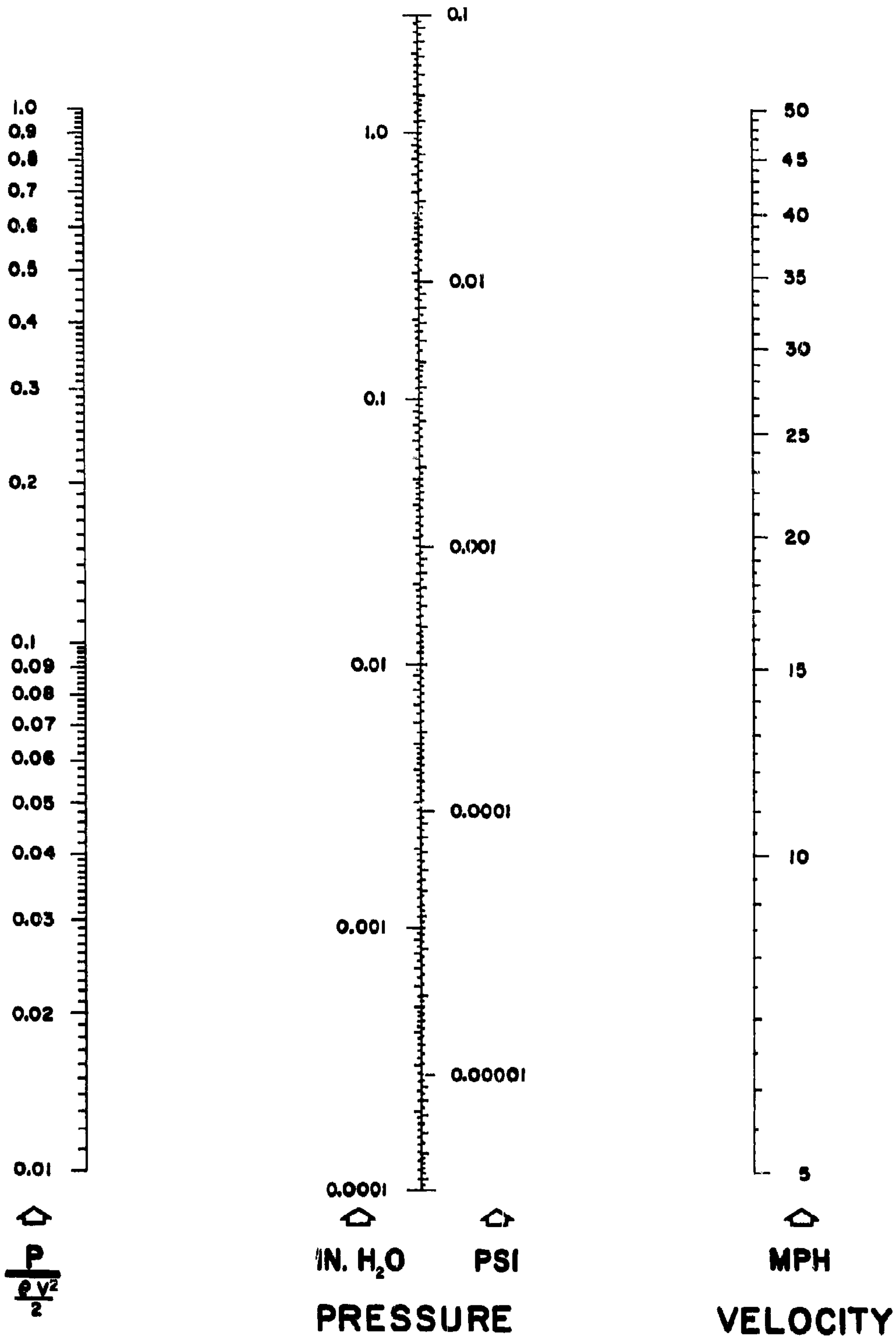




H/W = 1/2   θ = 45°



H/W = 1   θ = 45°

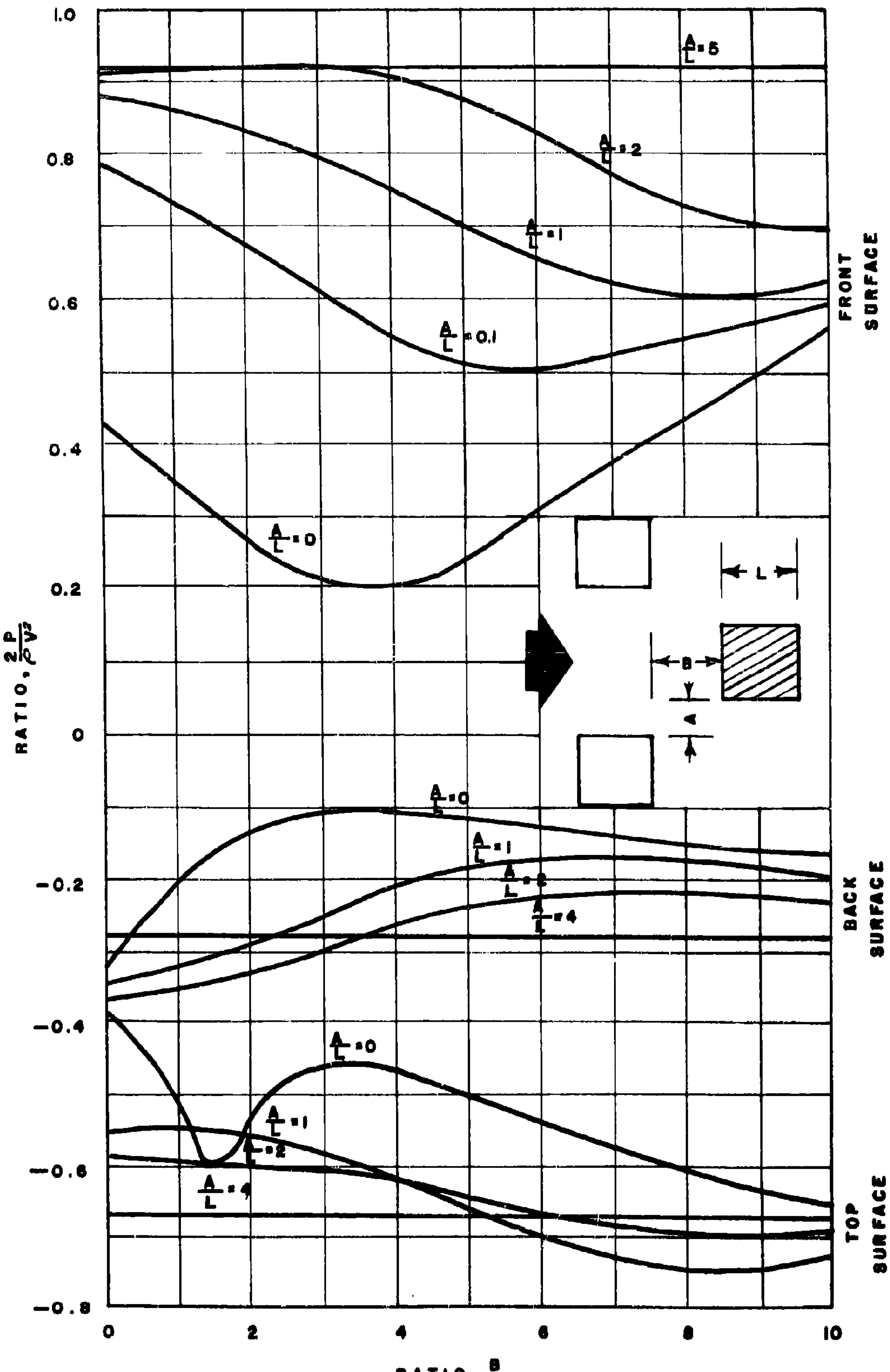


$$P = \left[\frac{P}{\rho V^2/2}\right]\left[\frac{\rho V^2}{2}\right]$$

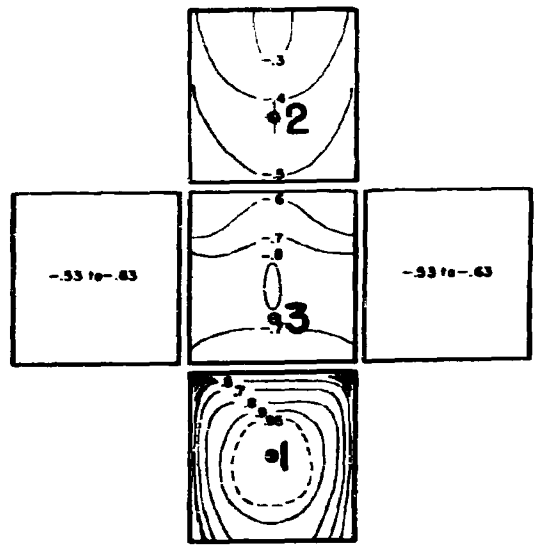
The nomograph is for standard air density of 0.075 lb_M per cu. ft. At sea level (29.92 in. of Hg barometric pressure) this is equivalent to dry air at 70 degrees F.

APPENDIX III

INFLUENCE OF OBSTRUCTIONS ON PRESSURE DISTRIBUTION



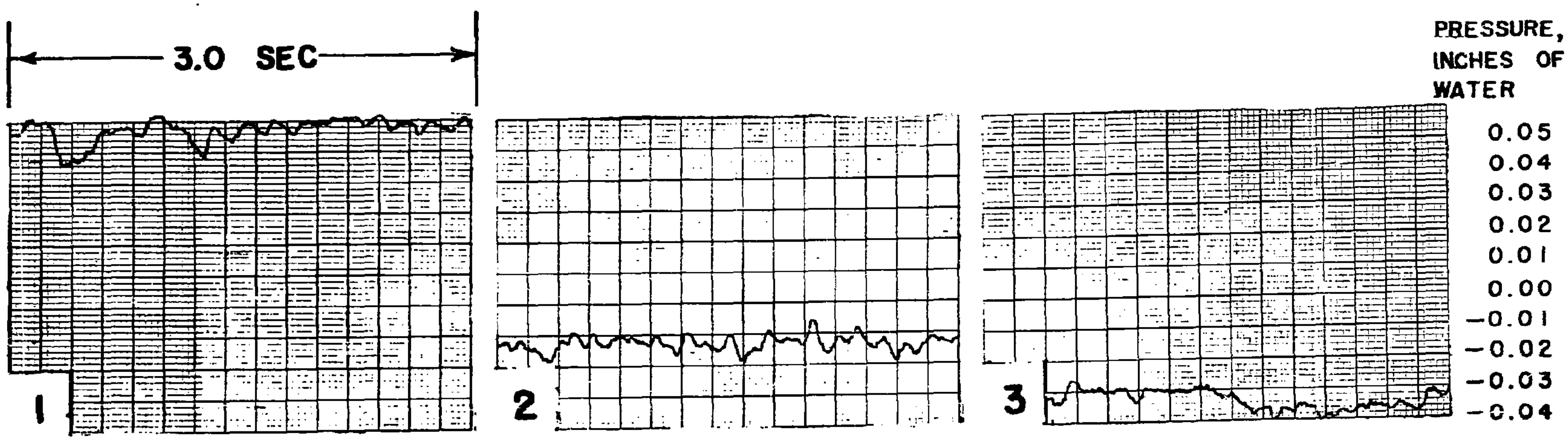
PRESSURE ON A CUBE WITH INTERFERENCE FROM TWO IDENTICAL CUBES



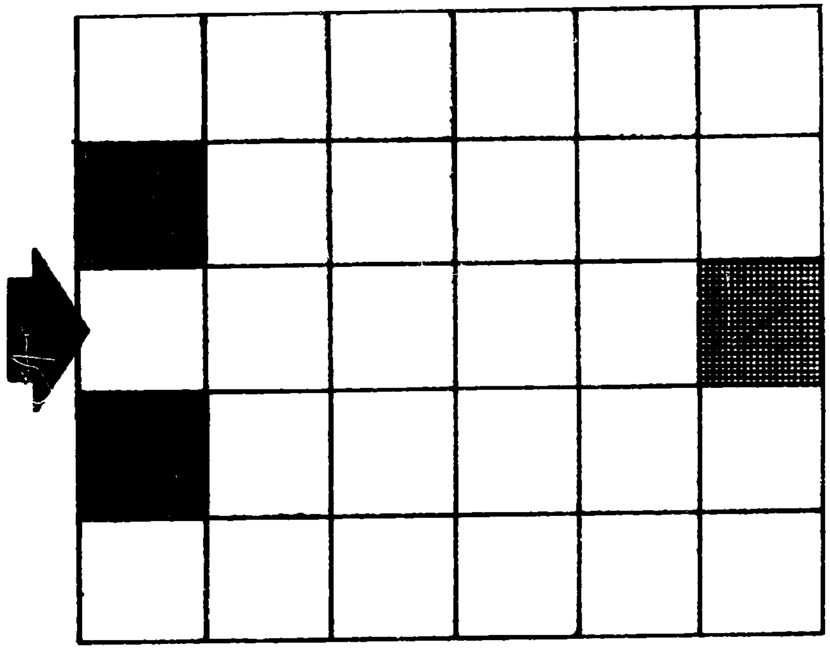
1:1:1

FIGURE 1

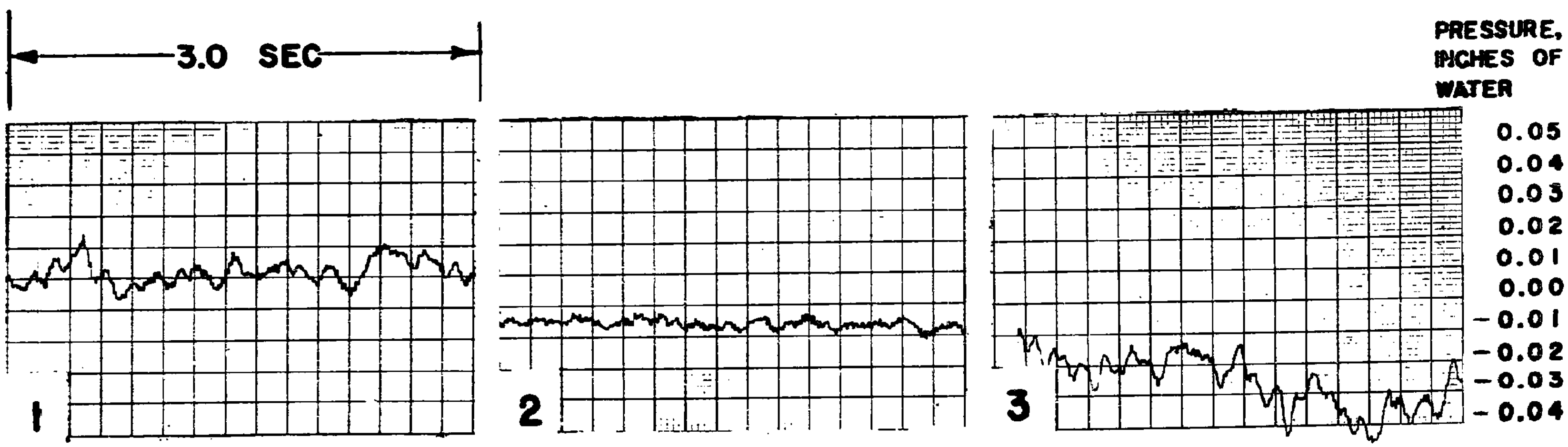
POINT	$\frac{P_{max}}{P_{min}}$	$\frac{V_{max}}{V_{min}}$
1	1.4	1.2
2	3.2	1.8
3	1.6	1.3



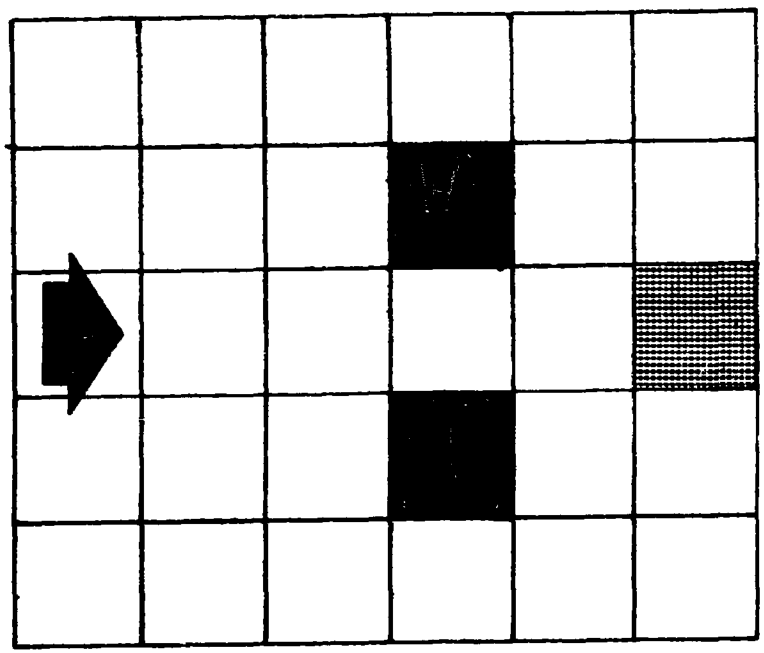
SURFACE PRESSURE ON A CUBE WITH NO LOCAL INTERFERENCE



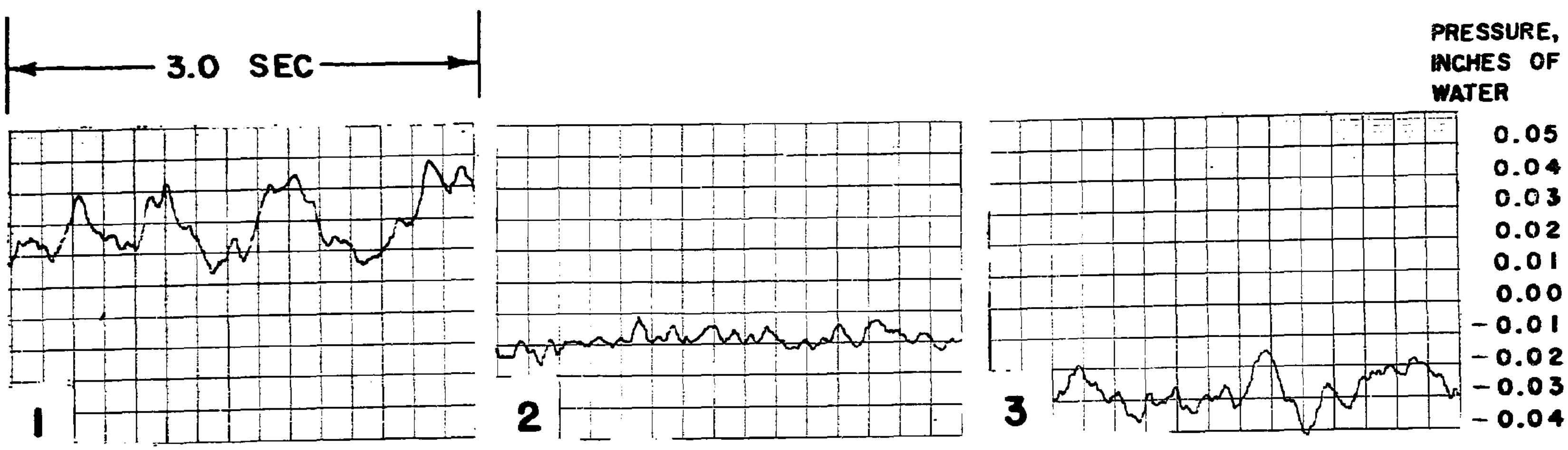
POINT	$\frac{P_{max}}{P_{min}}$	$\frac{V_{max}}{V_{min}}$
1	6.0	2.5
2	5.5	2.3
3	2.6	1.6



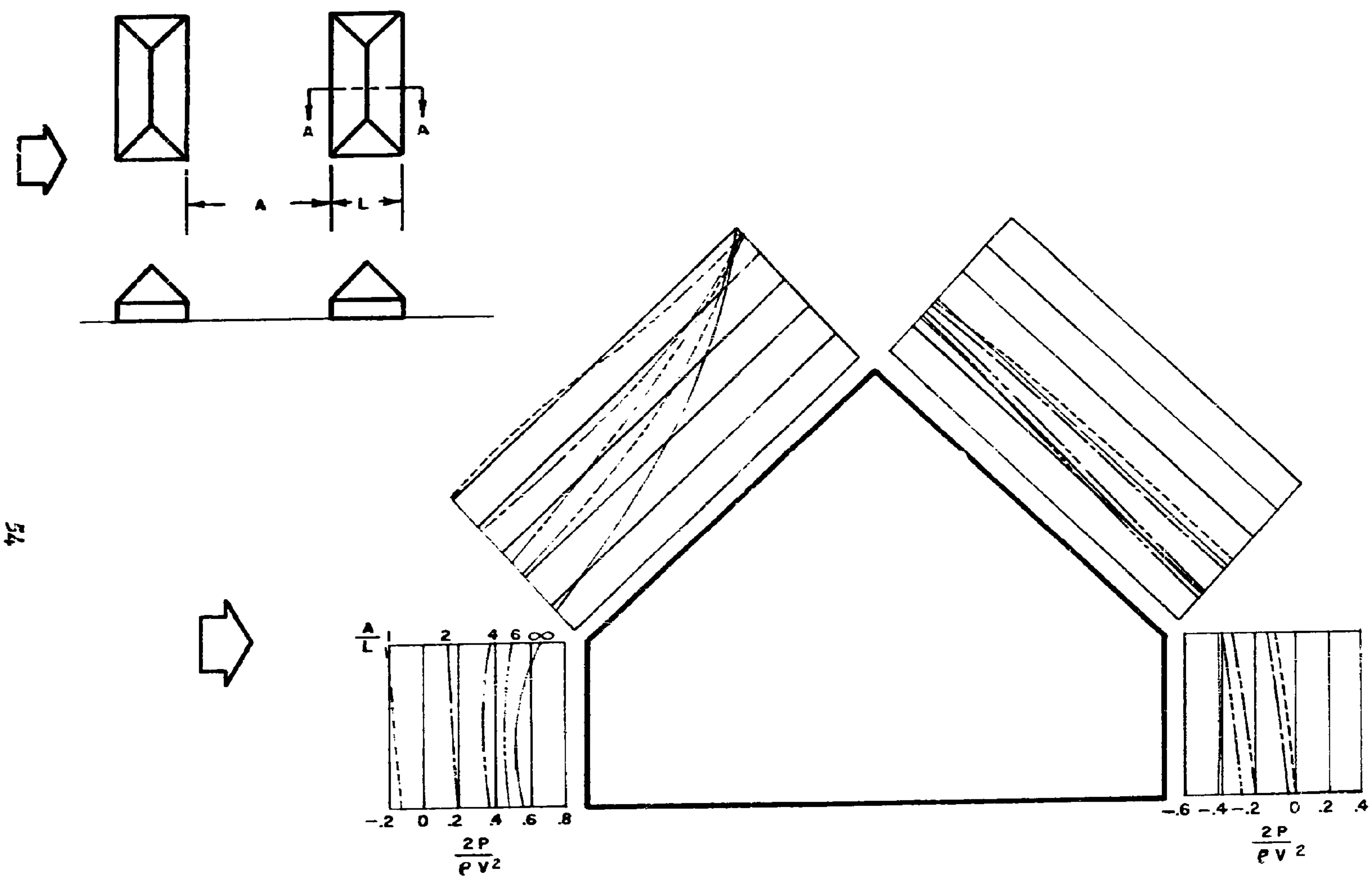
SURFACE PRESSURE ON A CUBE WITH INTERFERENCE FROM TWO IDENTICAL CUBES



POINT	$\frac{P_{max}}{P_{min}}$	$\frac{V_{max}}{V_{min}}$
1	3.4	1.9
2	8.0	2.8
3	2.8	1.7

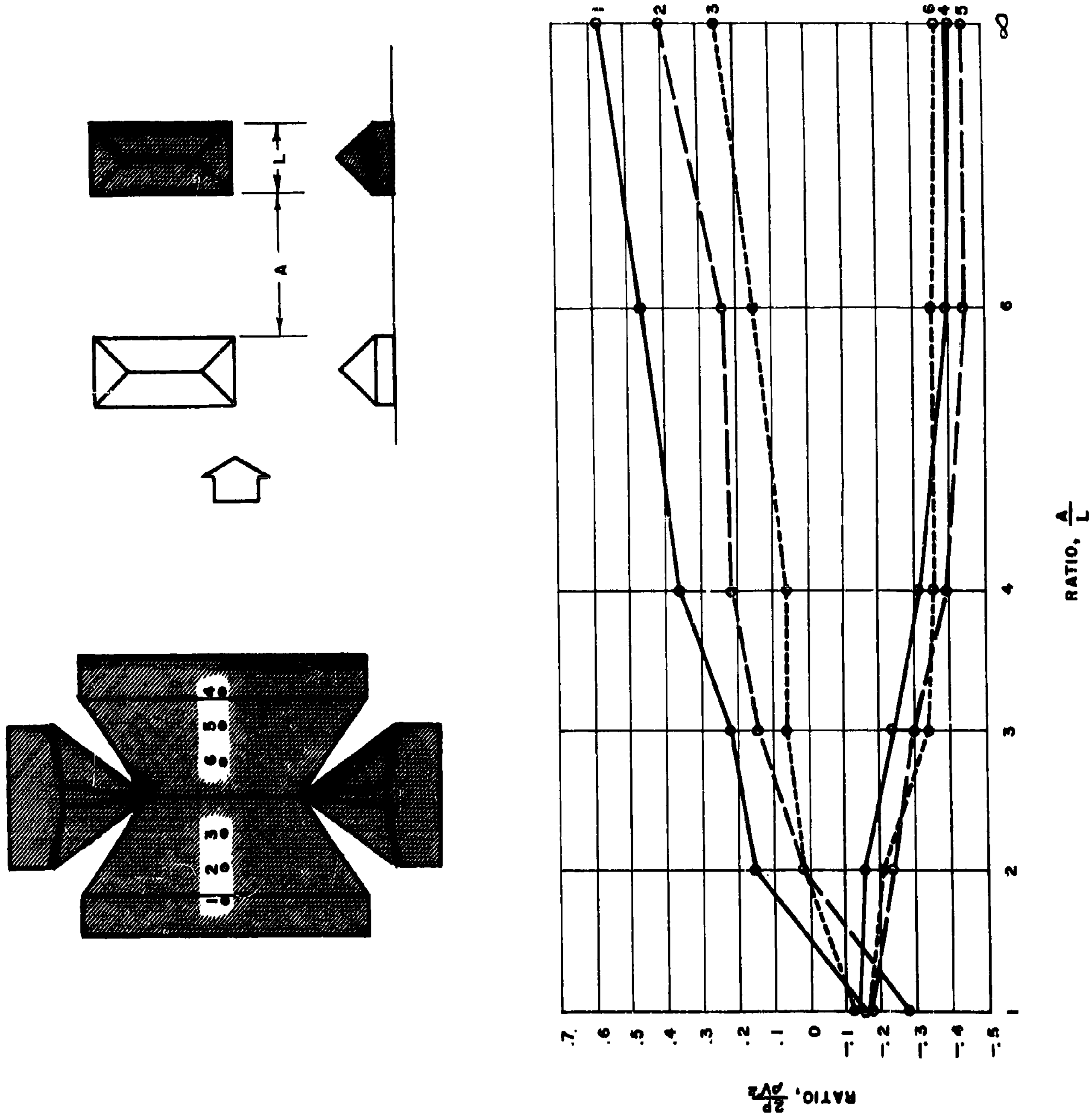


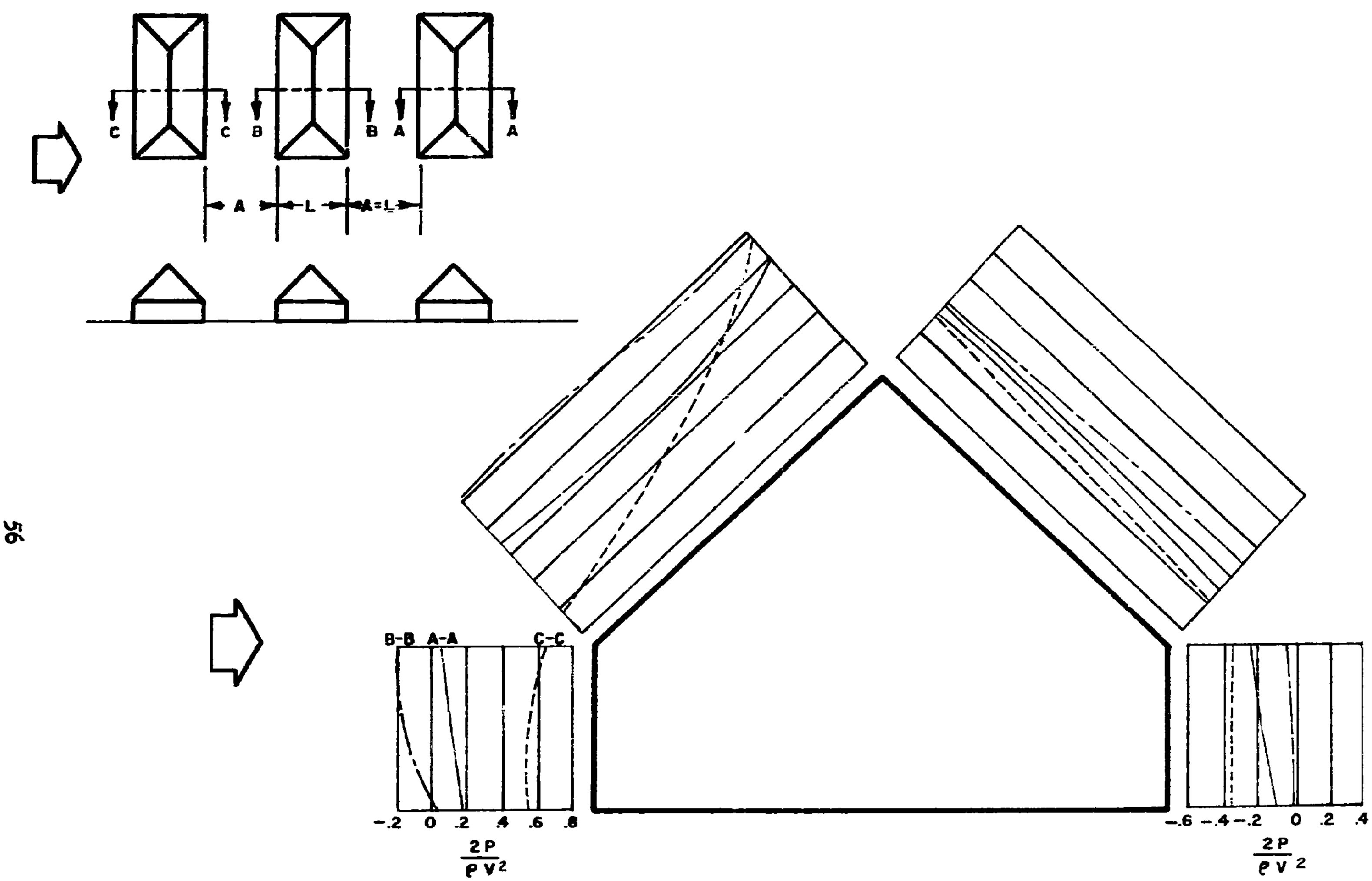
SURFACE PRESSURE ON A CUBE WITH INTERFERENCE FROM TWO IDENTICAL CUBES



PRESSURE DISTRIBUTION AT MID-SECTION OF U.S. ARMY SQUAD TENTS

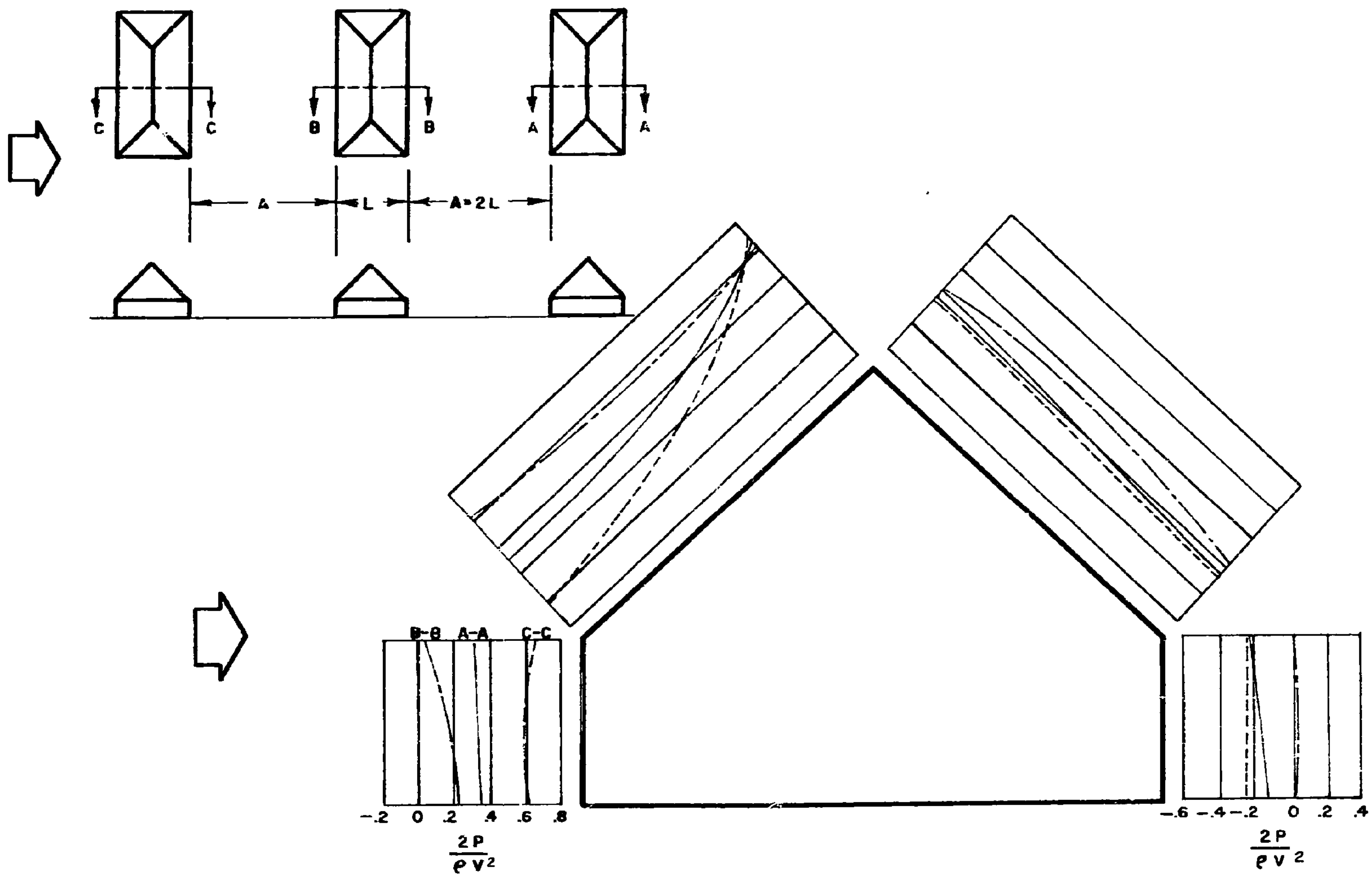
IN PROXIMITY OF OTHER TENTS


A
L
1 2 3
6 5 4
RATIO, $\frac{2P}{\rho V^2}$
RATIO, $\frac{A}{L}$



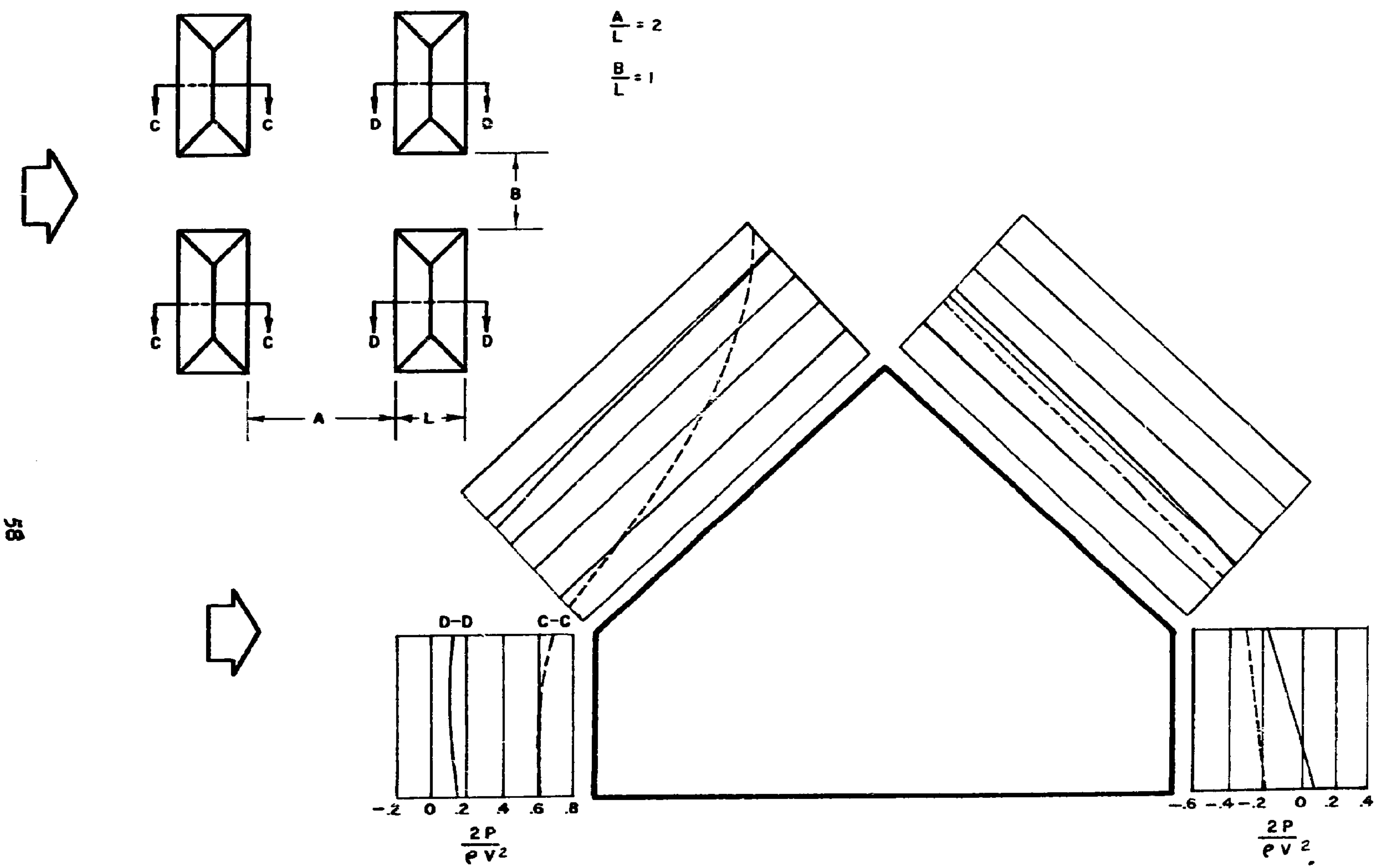
PRESSURE DISTRIBUTION AT MID-SECTION OF U.S. ARMY SQUAD TENTS

IN PROXIMITY OF OTHER TENTS



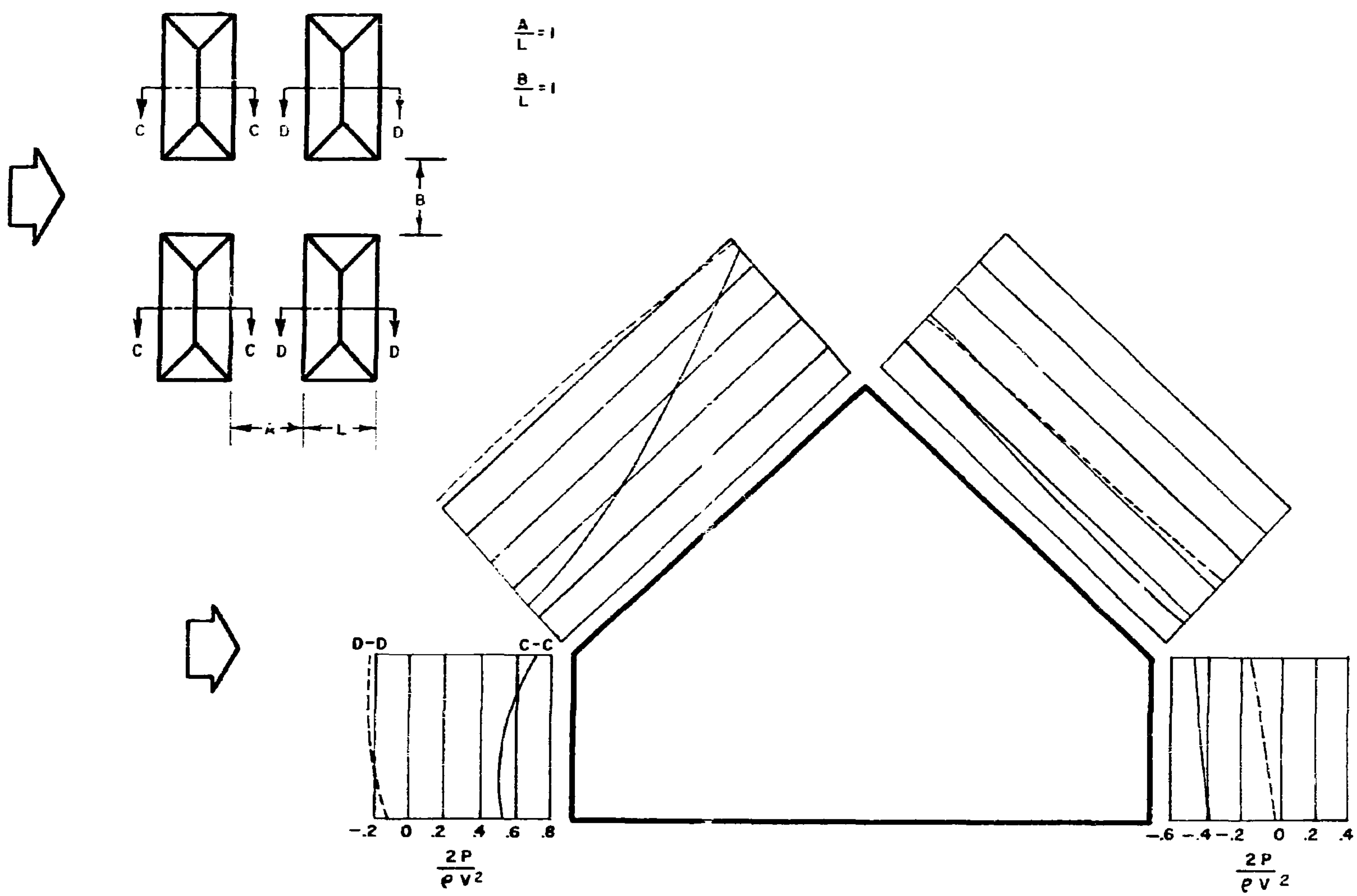
PRESSURE DISTRIBUTION AT MID-SECTION OF U.S. ARMY SQUAD TENTS

IN PROXIMITY OF OTHER TENTS



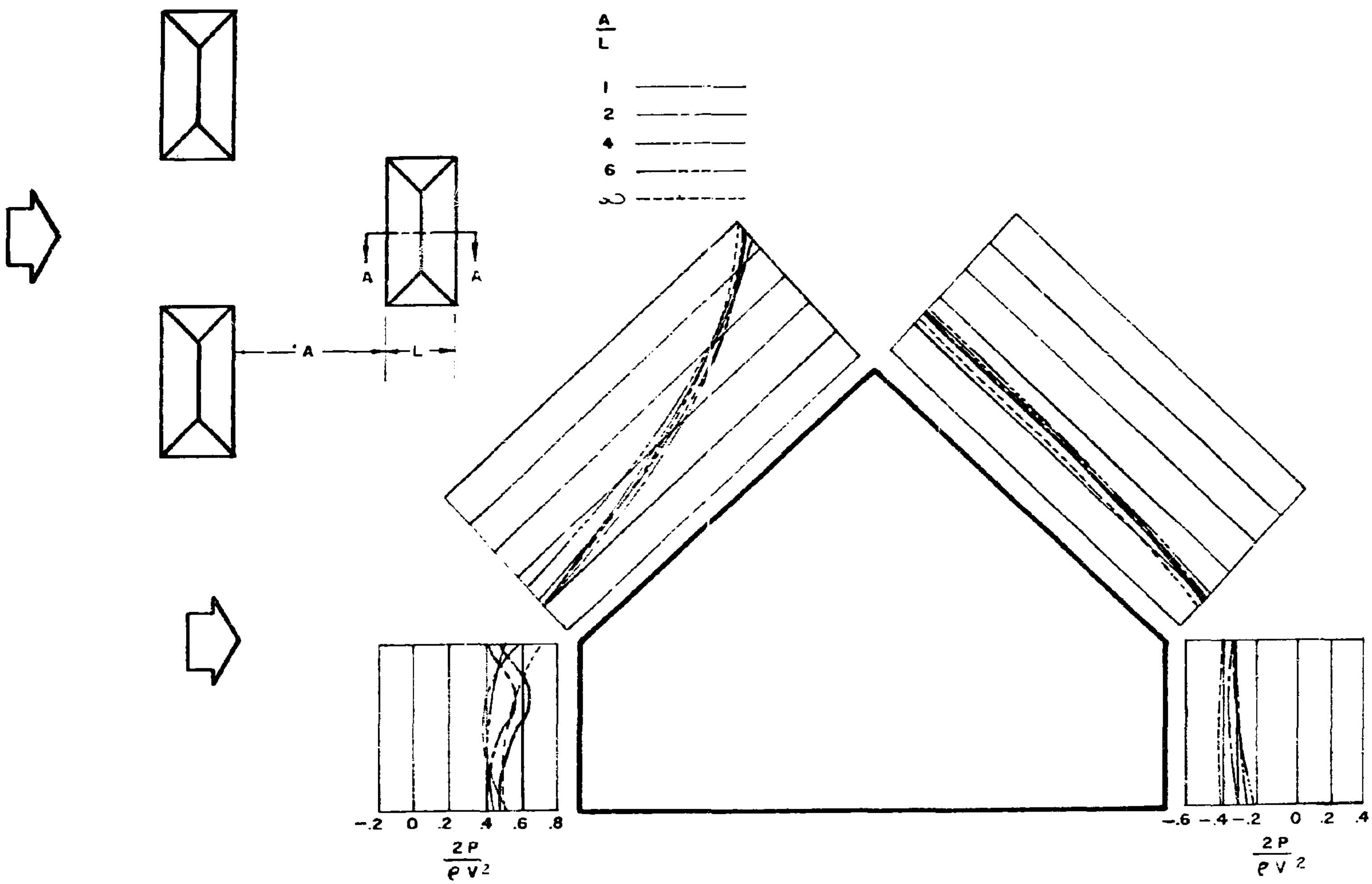
PRESSURE DISTRIBUTION AT MID-SECTION OF U.S. ARMY SQUAD TENTS

IN PROXIMITY OF OTHER TENTS



PRESSURE DISTRIBUTION AT MID-SECTION OF U.S. ARMY SQUAD TENTS

IN PROXIMITY OF OTHER TENTS

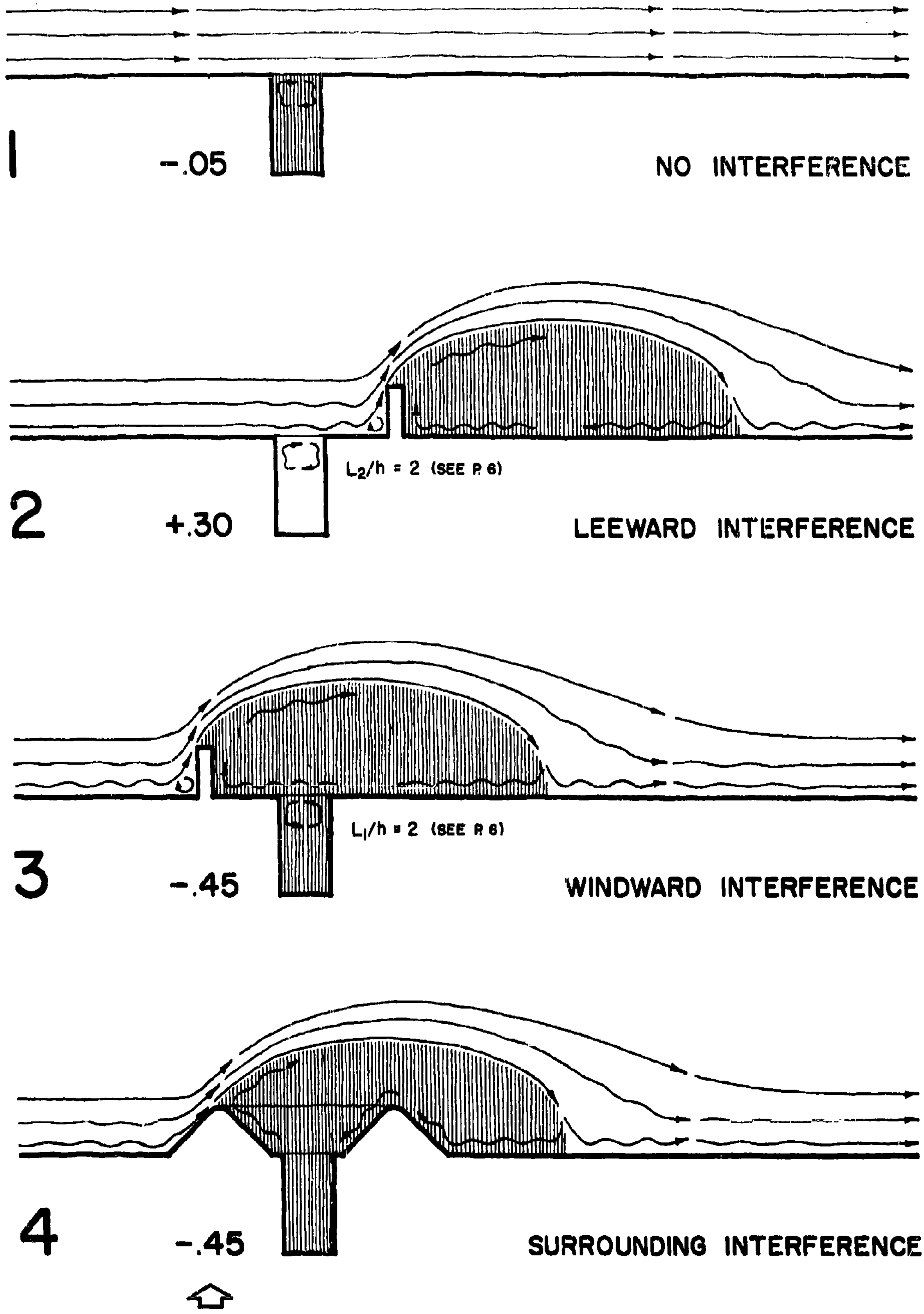


PRESSURE DISTRIBUTION AT MID-SECTION OF U.S. ARMY SQUAD TENTS

IN PROXIMITY OF OTHER TENTS

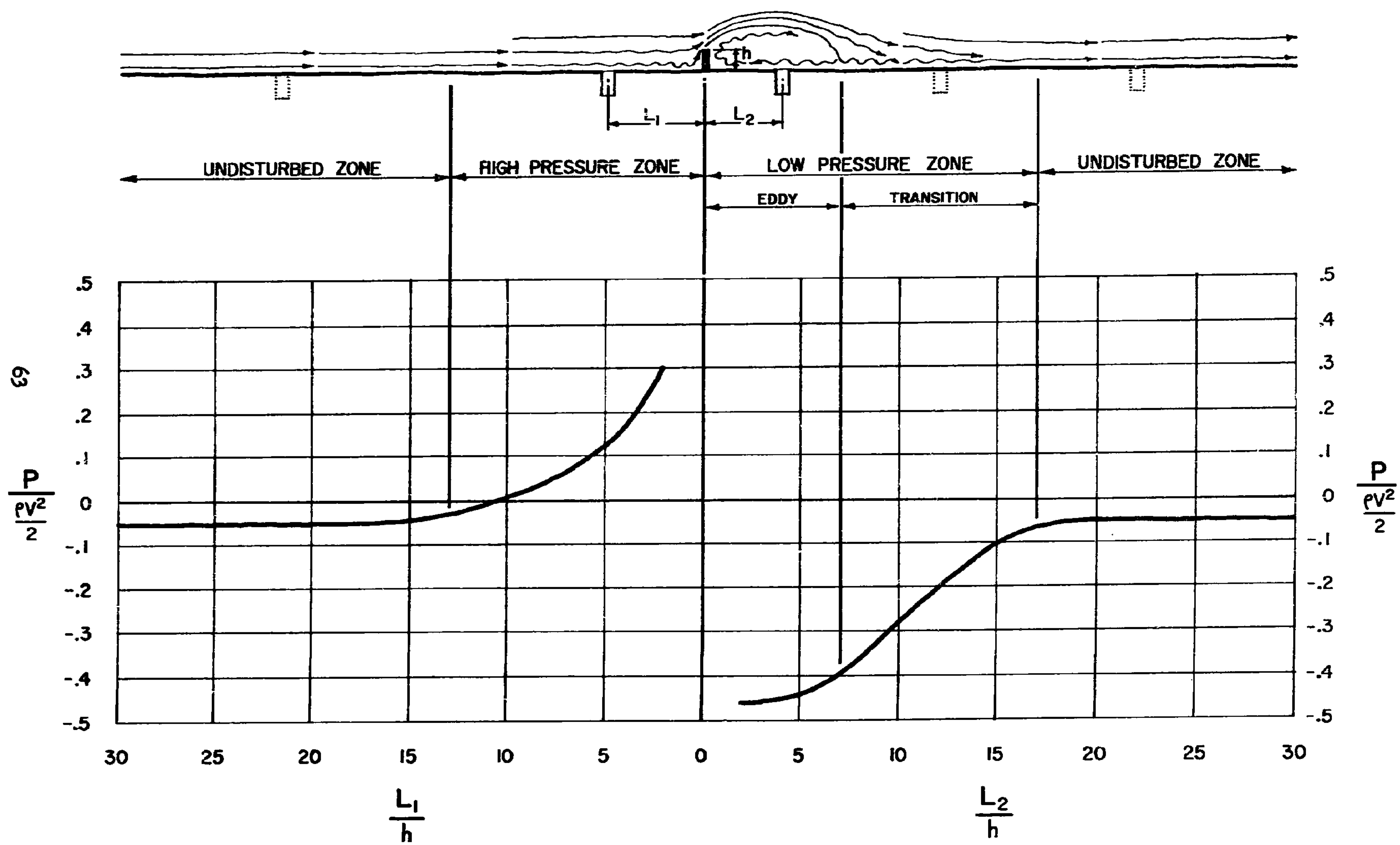
APPENDIX IV

PRESSURES IN ENTRANCES TO UNDERGROUND SHELTERS

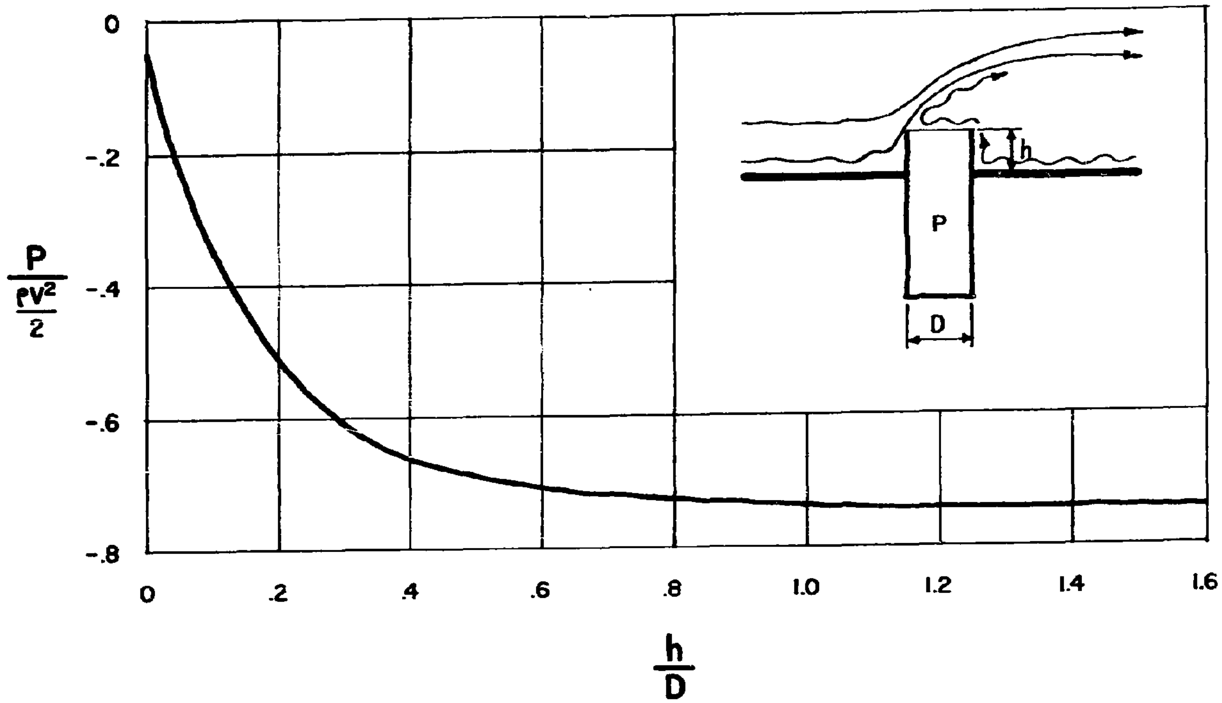


$$\frac{P}{\frac{\rho V^2}{2}}$$

AIR FLOW AROUND ENTRANCES TO UNDERGROUND SHELTERS



PRESSURE IN AND AIR FLOW AROUND ENTRANCES TO UNDERGROUND SHELTERS

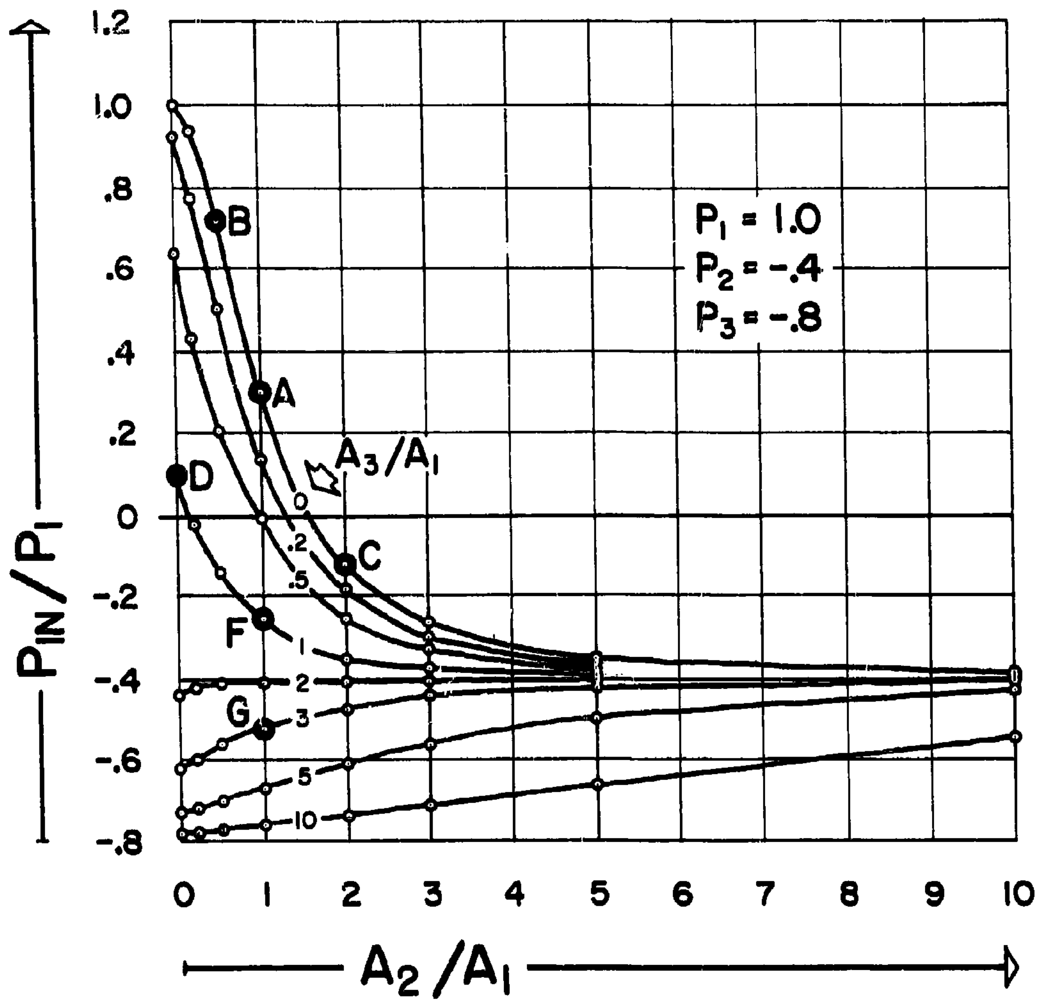


PRESSURE IN ENTRANCES TO UNDERGROUND SHELTERS
(WITH STACK)

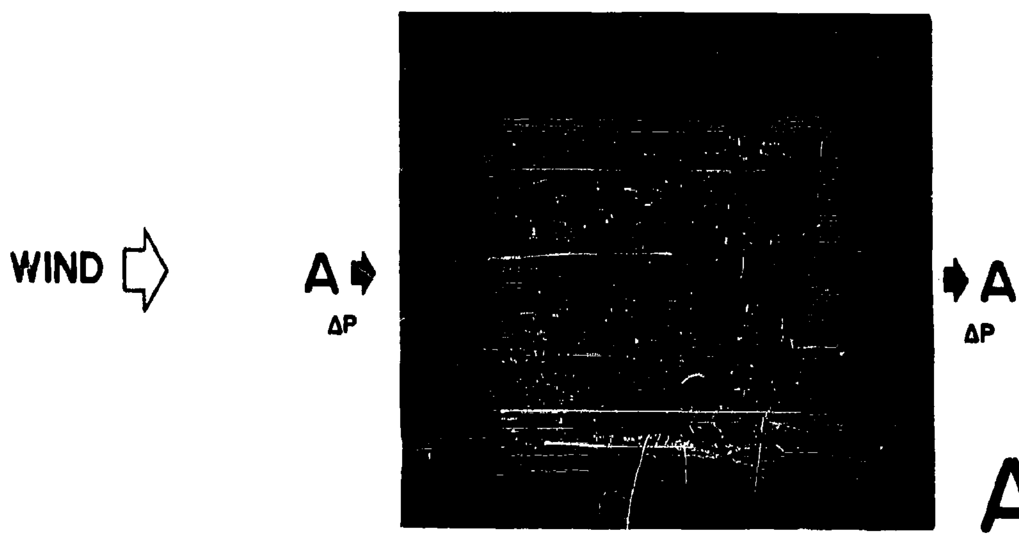
APPENDIX V

PRESSURES INSIDE BUILDINGS

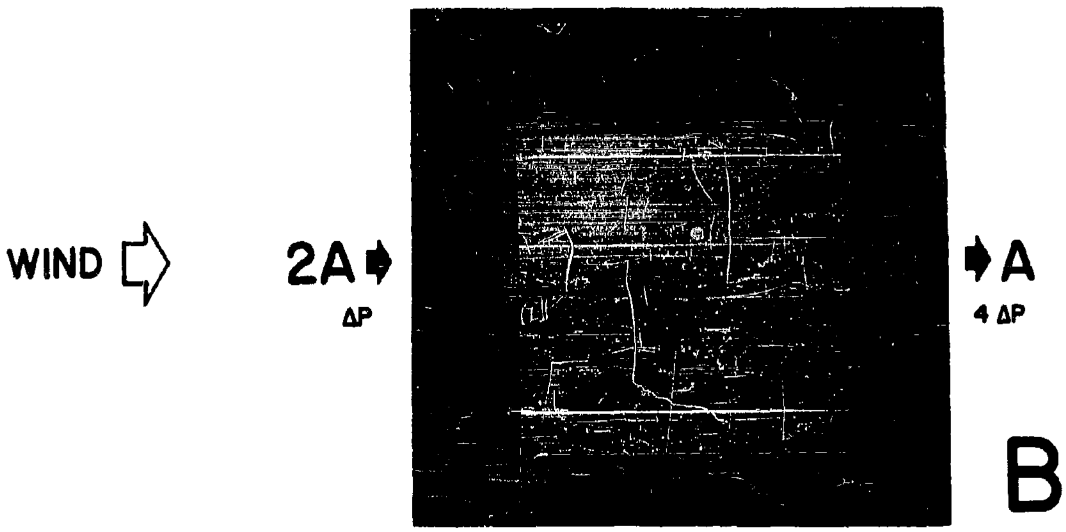
The curves below show the inside pressure for several area ratios with the given set of pressures outside the structure.

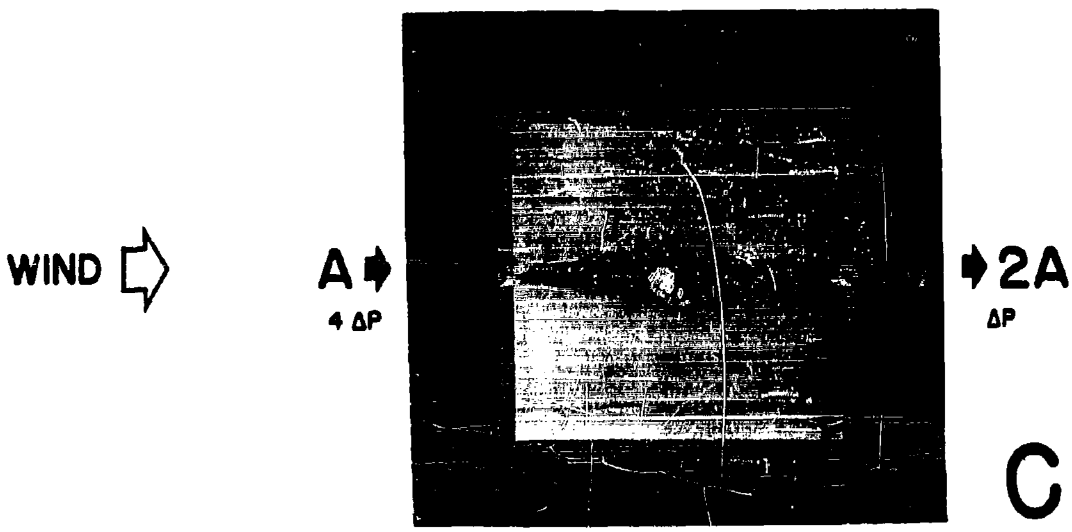


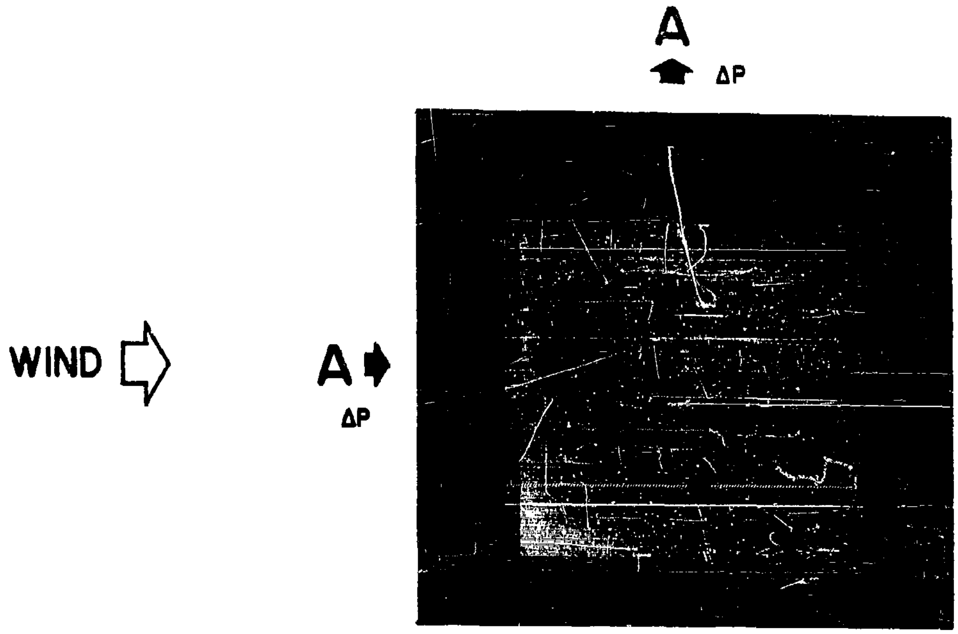
The following set of photographs illustrates several arrangements of openings. The photographs are designated by letters A through G so that the area ratios, pressure ratios, and the pressure inside the building can be found on the curves on pages 8 and 66. (Photos by Roland Chatham.)



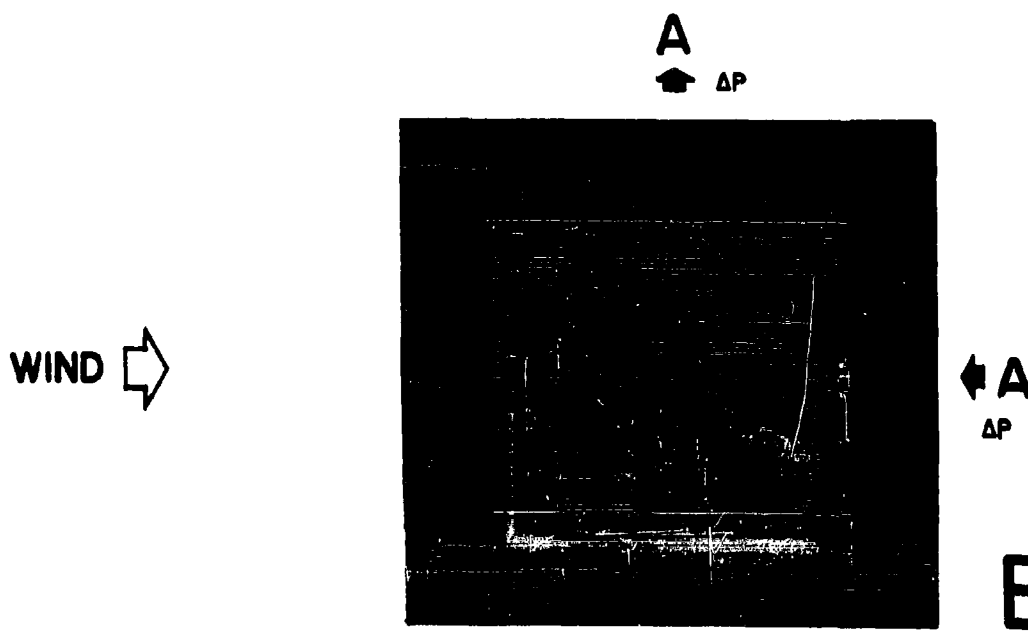
A


WIND
2A
ΔP
A
4 ΔP
B

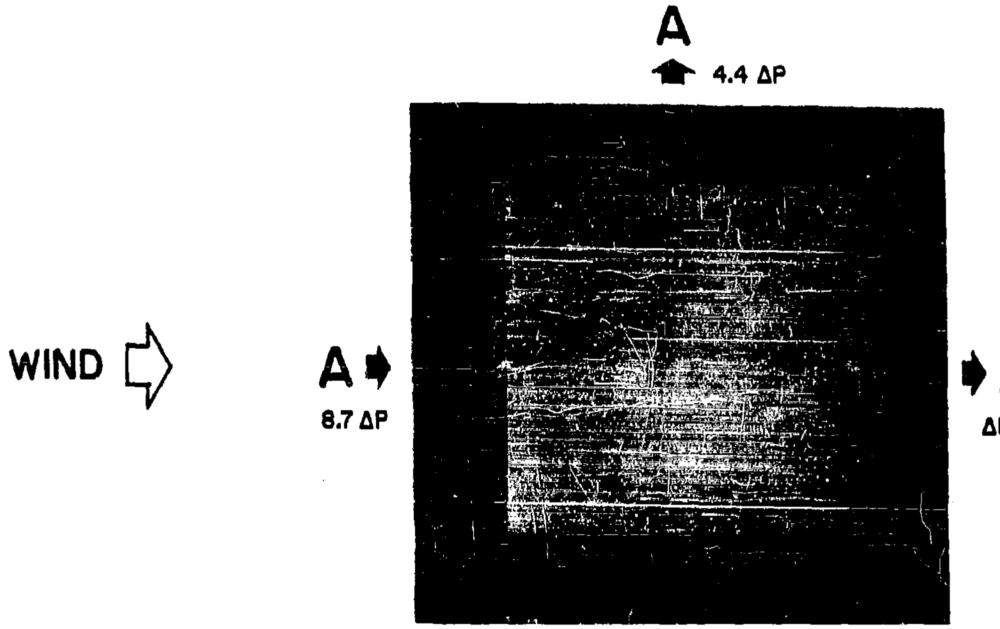

WIND
A
4 ΔP
2A
ΔP
C



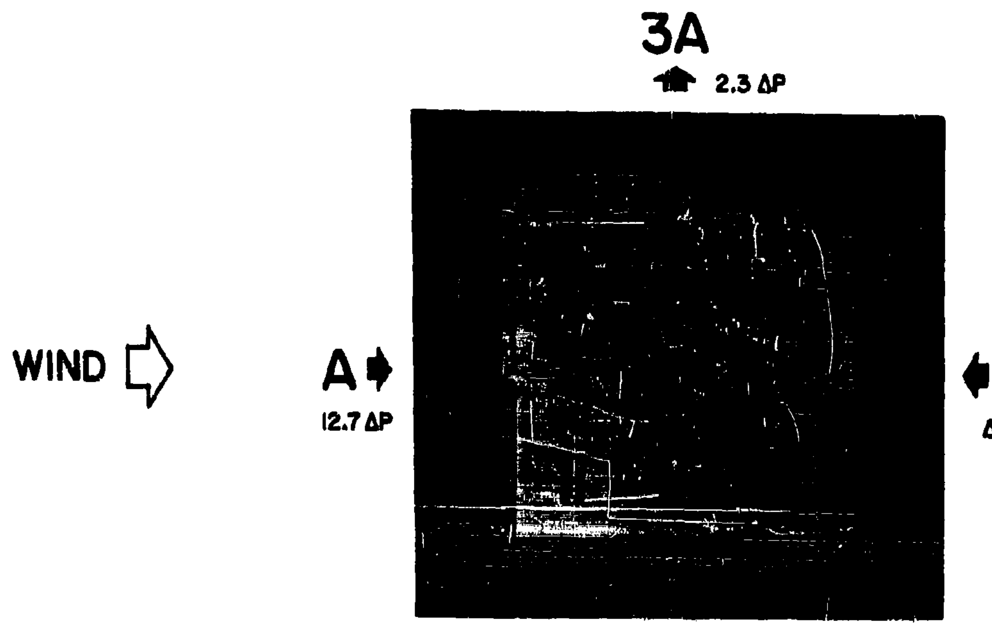
D



E



F



G

APPENDIX VI

WIND CHARACTERISTICS AND MINIMUM EFFECTIVE GUST

WIND CHARACTERISTICS

When determining the design wind on a structure at a given location, it is necessary to select the maximum wind velocity that is probable to occur in a given number of years. The only continuous long-time records of wind velocity for all parts of the United States are those of the U. S. Weather Bureau. These records are based on 5-minute average wind velocity and there are little data on peak winds or gusts. Before these records can be used to determine the maximum probable wind, it is necessary to convert the wind at the elevation of the anemometer to the elevation at which we are concerned, and to find a relationship between the peak wind and the mean 5-minute wind.

The U. S. Weather Bureau records can be used to prepare a statistical curve to show the strongest wind likely to occur in any given period. The theory of extreme value is the best known procedure to use for this type data.(1)* The values are shown in Fig. 1 for some typical stations. When the recurrence interval is greater than 10 years, the ratio of the design return period to the desired lifetime for various calculated risk is:

Calculated Risk:	0.63	0.50	0.40	0.30	0.25	0.20	0.10	0.05
$\frac{\text{Design Return Period}}{\text{Desired Lifetime}}$:	1.00	1.44	1.96	2.80	3.45	4.48	9.49	19.50

A structure which is to last 25 years with a calculated risk of twenty percent that it will not fail due to strong winds in less than that time, should be designed for the strongest probable wind that will occur in 4.48 X 25 years = 111 years. For a probability of ten percent

* Numbers refer to references on page 76.

the time would be 9.49 X 25 years = 237 years.

The relationship between the peak wind or gust and the mean 5-minute wind has been analyzed for several storms.(2)(3) The difference between the peak velocity and the 5-minute velocity does not change much with mean velocity or elevation. (2)(3) Therefore, the ratio of peak wind to the 5-minute wind (gust factor) is greater for the lower mean wind. Fig. 2 shows the relationship between the gust factor and the 5-minute wind. A gust factor of 1.34 can be used for all winds with a mean velocity above 50 miles per hour.

The most common equation used to describe the variation of velocity with height is:

$$\frac{V_2}{V_1} = \left[\frac{H_2}{H_1}\right]^a$$

where V_1 and V_2 are the wind speeds at heights H_1 and H_2 respectively, and "a" is a constant depending upon the atmospheric turbulence. Various investigators have found "a" to vary from 0.1 to 0.4. Collins (3) found that "a" is a function of the wind velocity at 30 ft. height and suggests the following relationship:

Average Wind at 30 ft.	"a"
10 Mph	0.19
20	0.21
30	0.23
40	0.25
50	0.27
60	0.29
70	0.31

Fig. 3 is a plot of the equation using the values of "a" given above.

When the maximum 5-minute wind at a given height and the gust factor are known, the velocity pressure can be calculated from the equation:

$$V.P. = \frac{\rho \ V_m^2}{2} = \frac{\rho(FV)^2}{2}$$

where V_m is the maximum wind velocity and is equal to the gust factor, F, times the 5-minute velocity, V, and ρ is the density of the air. From Fig. 2, $F = \frac{3.3}{V^{0.23}}$ when $V \leq 50$ miles per hour. Now the equation becomes:

$$V.P. = \frac{k\rho}{2}\left[\frac{3.3V}{V^{0.23}}\right]^2$$

where V.P. is the velocity pressure in pounds force per sq. ft., ρ is the air density in pounds mass per cubic ft., and V is the mean 5-minute velocity in miles per hour.

When $V > 50$ miles per hour, $F = 1.34$. Then the equation becomes:

$$V.P. = \frac{k\rho}{2}(1.34 \ V)^2 = 0.0596 \rho V^2$$

This velocity pressure is shown at the right side of Fig. 3.

MINIMUM EFFECTIVE GUST

In order to determine the minimum effective gust, it is necessary to measure the relationship between the wind velocity and the building pressure. A gust that is a small fraction of the size of the structure will not produce the maximum wind load on the structure. The gust must be of sufficient size to envelop the structure and the flow pattern on both the windward and leeward sides of the structure.(2) This gust size has been shown to be about eight times the dimension of the building along the wind direction.

When it is desired to prevent infiltration into a building, it is necessary to find the wind velocity and building pressure relationship for each point on the faces of the building. Figures 4 through 6 are oscillograph records of the velocity pressure, $\frac{\rho V^2}{2}$, and the pressure at two points on the face of a cube.

It can be seen there is no time lag between the pressure rise on the impact tube and the windward face of the cube. In fact the pressure wave reaches the model building about 0.1 second before it reaches the pitot tube and is slightly higher than the velocity pressure. The time lag on the top face is about 0.5 sec. for a six inch cube when the wind velocity is 15 ft. per sec. The wind travels 7.5 feet before the maximum wind load is produced. This is 15 times the size of the structure.

The pressure rise at a point on the windward side of a building will respond to a gust of any size or duration. There is no time lag because of the building geometry. It would be necessary to pressurize a building to a pressure equal to the dimensionless pressure coefficient, $P/\frac{\rho V^2}{2}$, times the maximum gust velocity pressure that is probable to occur at the location of the building if it is desired to prevent infiltration.

EXAMPLE

It is desired to find the velocity pressure 25 feet above ground elevation at Duluth, Minn. Other data are:

Anemometer height	47 feet
Desired lifetime of structure	20 years
Calculated risk	10 %

For a calculated risk of 10 % the design return period is 9.49 X 20 years = 190 years.

From Fig. 1, the 5-minute velocity is 72 miles per hour for a return period of 190 years.

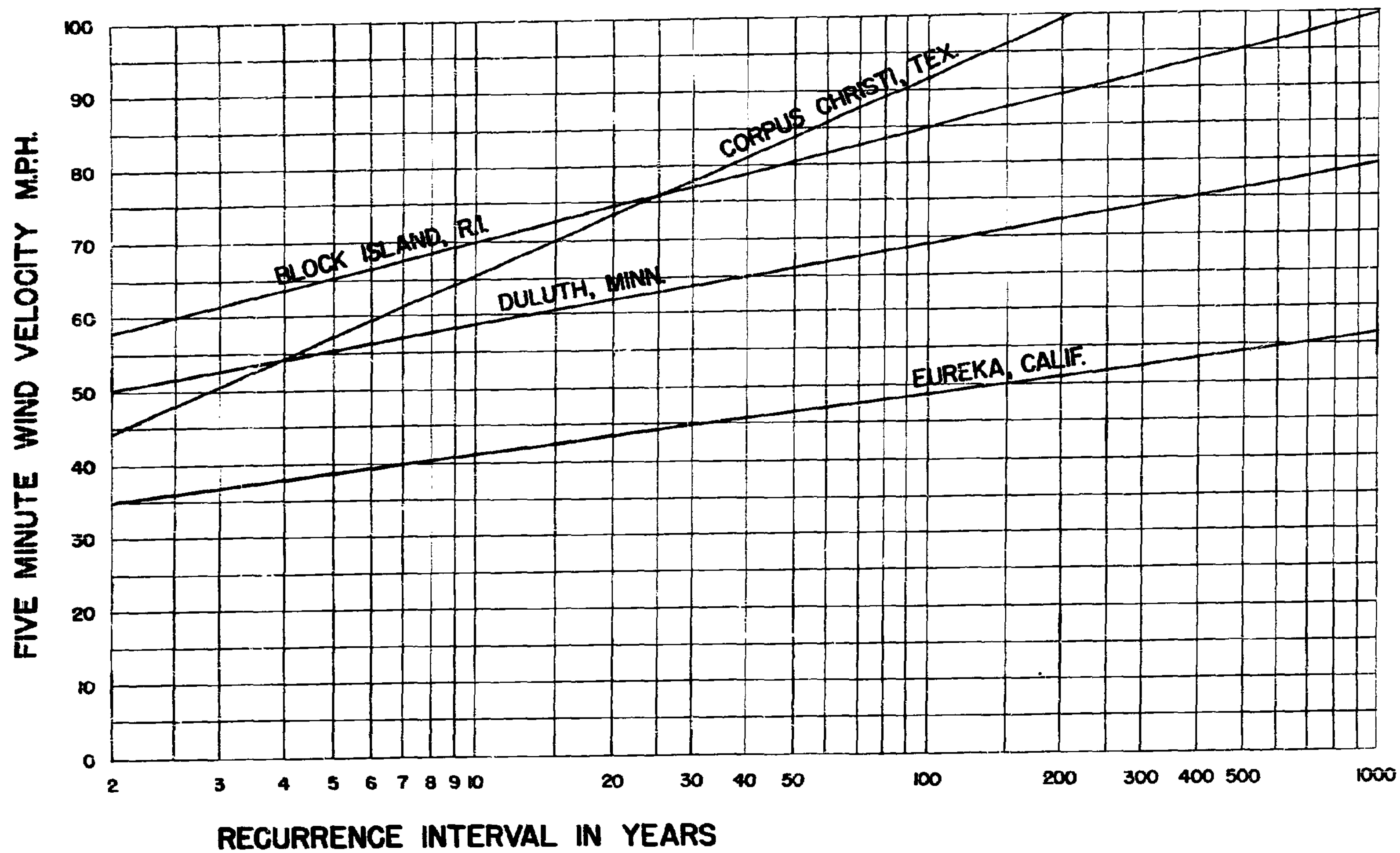
From Fig. 3, the velocity at an elevation of 25 feet is found to be 59 miles per hour, and the velocity pressure of the gusty wind is 2.95 inches of water or 15.5 pounds per sq. ft.

REFERENCES

1. Arnold Court, "Wind Extremes as Design Factors," Journal of The Franklin Institute, vol. 256, 1953, p. 39.

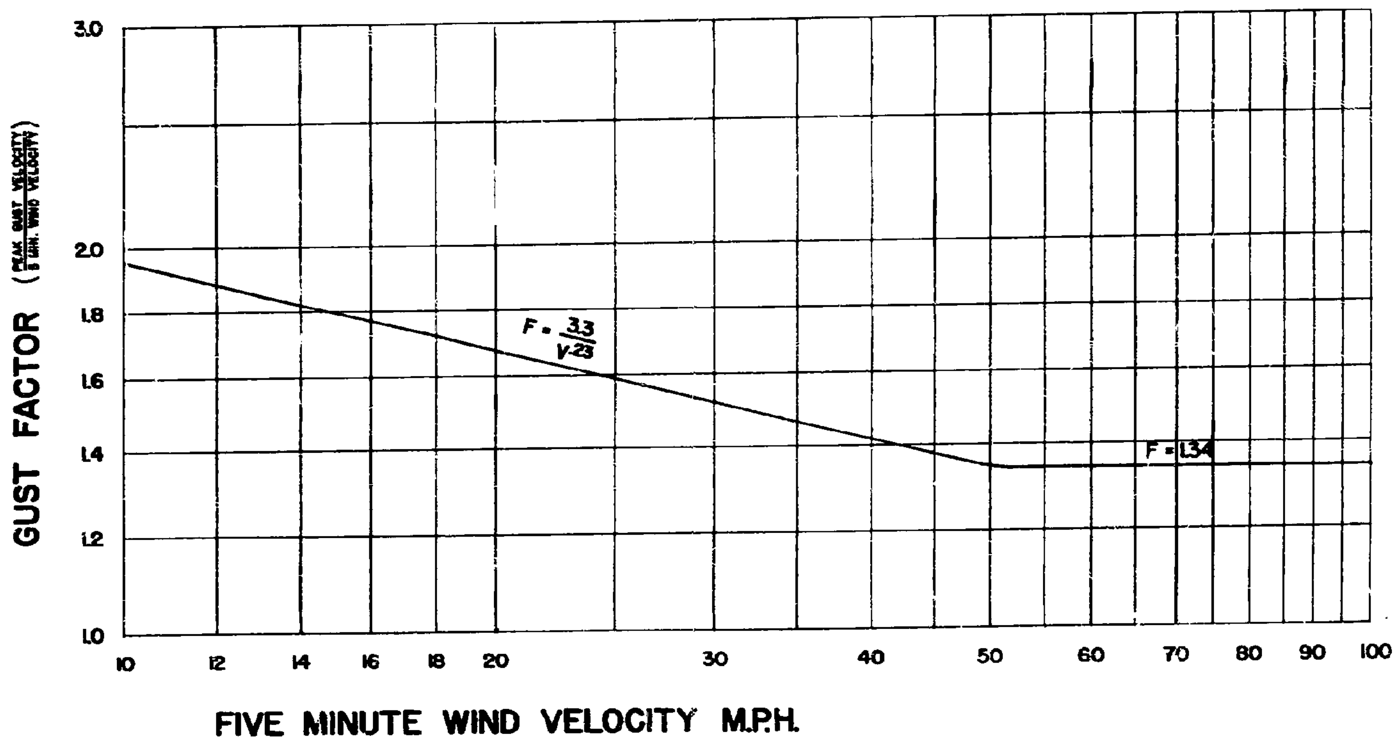
2. R. H. Sherlock, "Variation of Wind Velocity and Gust With Height," Transactions of The American Society of Civil Engineers, vol. 118, 1953, p. 463.

3. George F. Collins, "Determining Basic Wind Loads," Proceedings of The American Society of Civil Engineers, Paper No. 825, 1955.



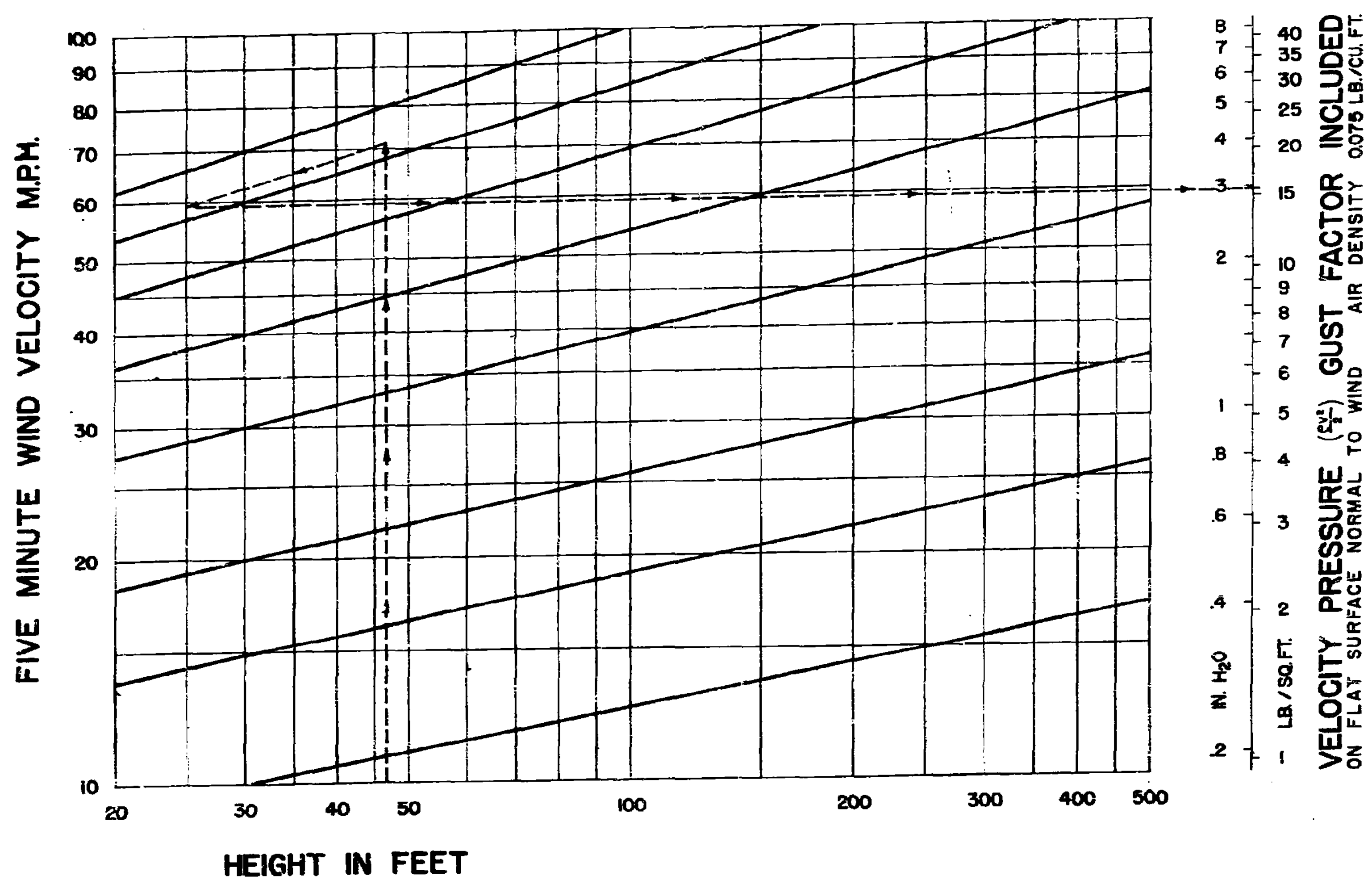
STRONGEST FIVE MINUTE WIND EXPECTED
IN INTERVALS OF FROM 2 TO 1000 YEARS

FIG. I



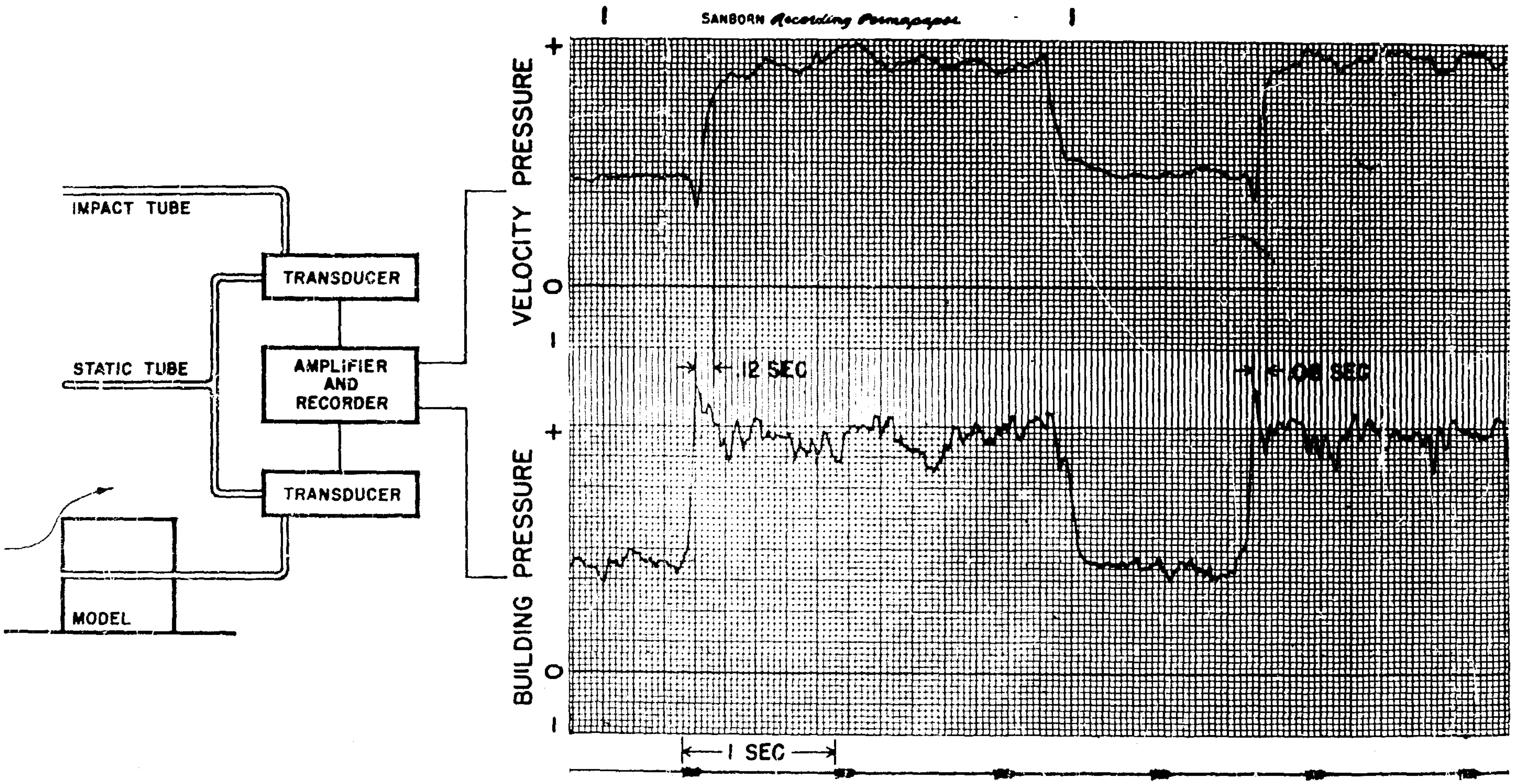
RELATIONSHIP BETWEEN GUST FACTOR AND FIVE MINUTE WIND VELOCITY

FIG. 2



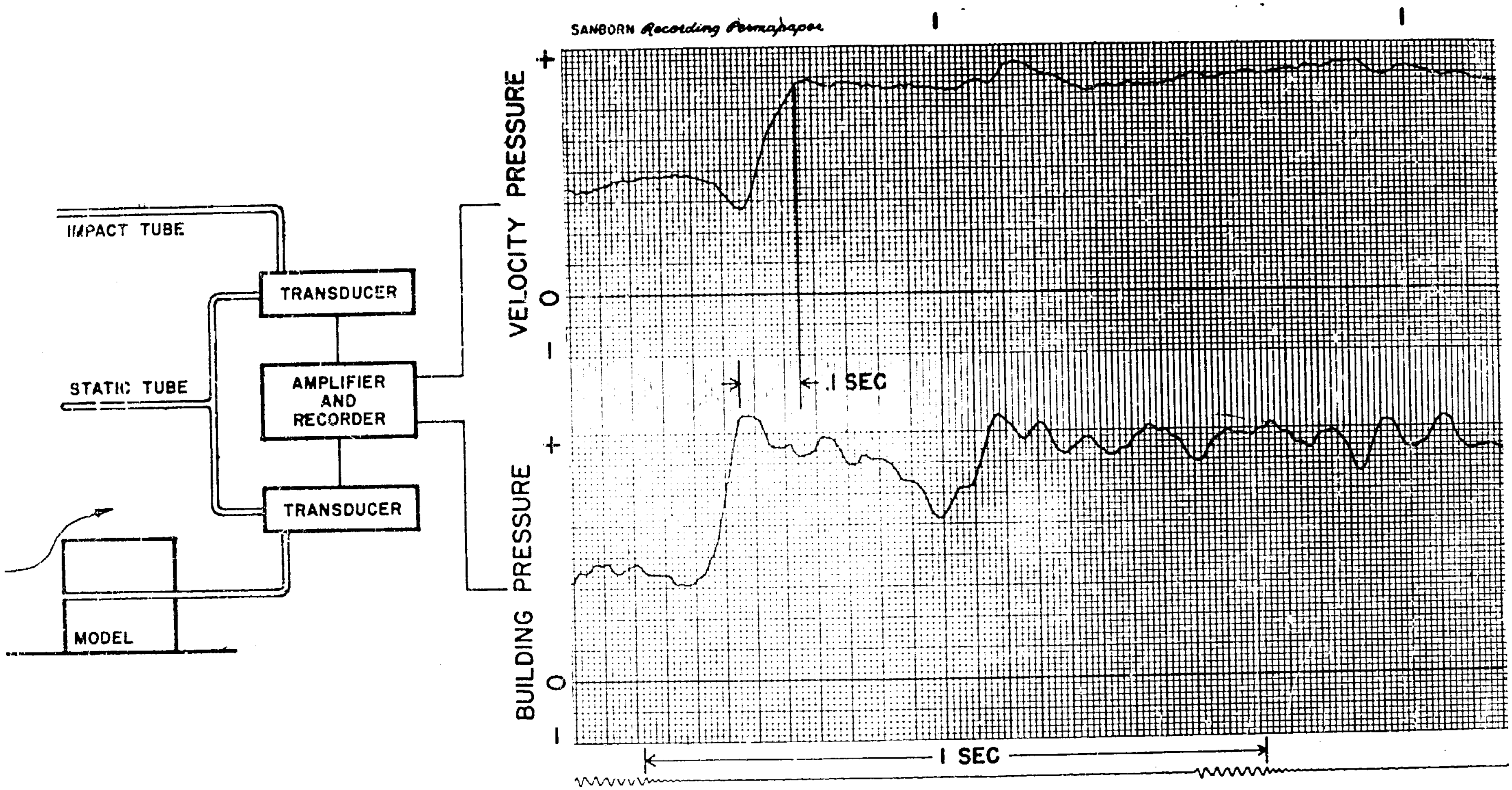
RELATIONSHIP BETWEEN FIVE MINUTE WIND VELOCITY, HEIGHT AND VELOCITY PRESSURE

FIG. 3



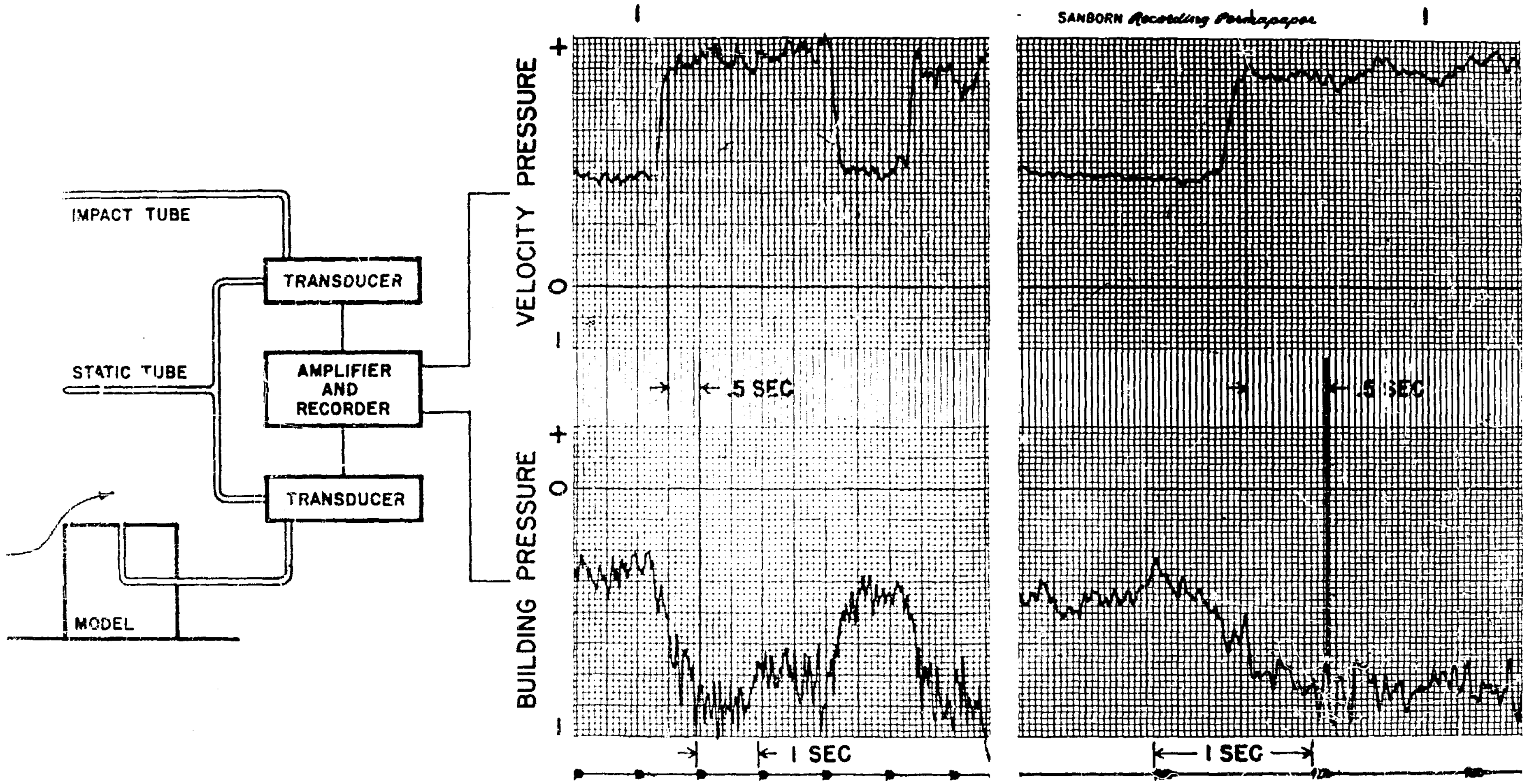
PRESSURE-TIME RELATION FOR GUSTS ON WINDWARD FACE OF STRUCTURE

FIG. 4



PRESSURE - TIME RELATION FOR GUSTS ON WINDWARD FACE OF STRUCTURE

FIG. 5



PRESSURE - TIME RELATION FOR GUSTS ON UPPER FACE OF STRUCTURE

FIG. 6